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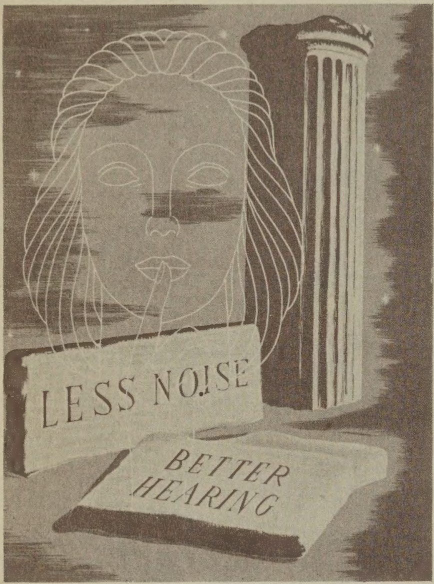
LESS NOISE
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SIXTH EDITION

THE CELOTEX CORPORATION

120 S. LA SALLE STREET CHICAGO

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LESS NOISE · BETTER HEARING

An Outline of the Essentials of Architectural Acoustics for the Practising Architect and Engineer

Prepared under supervision of

Hale J. Sabine

Chief Acoustical Engineer

THE CELOTEX CORPORATION

120 S. LaSalle Street Chicago 3, Illinois

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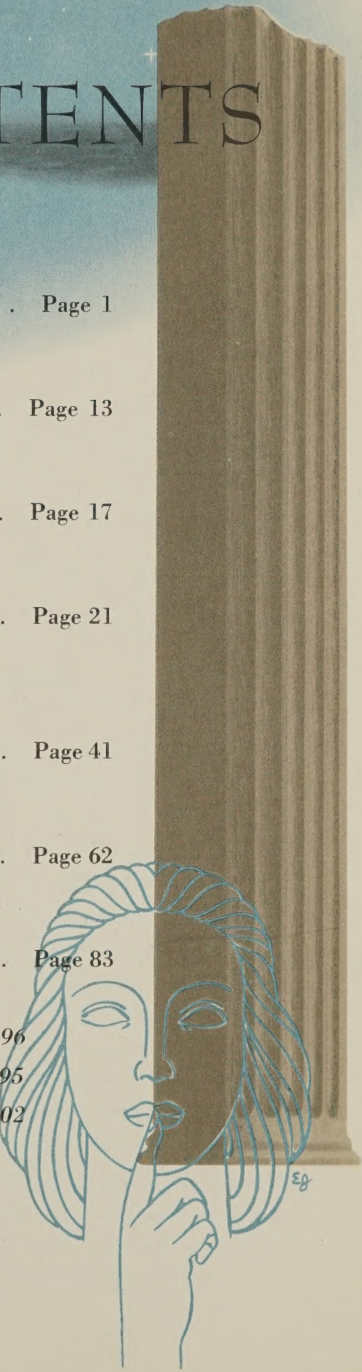

2000 YEARS AGO VITRUVIUS, Roman Architect

said... "A GOOD BUILDING MUST BE BUILT WELL , WORK WELL AND LOOK WELL"...

Unlike truth, building construction has changed in the two thousand years since Vitruvius gave expression to this precept of good architecture.

Modern structures, modern materials, modern equipment have made common a need for sound-absorbing interior finish—*acoustical treatment.*

This need has been met by American inventive genius. In the development of a variety of acoustical materials, The Celotex Corporation has been privileged to play an important part.

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Useful knowledge in science grows with practical experience. Such experience in the field of architectural acoustics consists in the number and variety of problems dealth with. To develop this experience rapidly, The Celotex Corporation in 1925 chose to seek out, school, and establish in all principal market centers an authorized engineering, sales, and contract service by independent, locally owned and operated enterprises.

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Airlines Terminal Building, New York City. Celotex acoustical treatment eliminates loud and annoying reverberation. Architect: John B. Peterkin.

Chapter I

Physics of Sound

SOUND IS DEFINED as a wave motion in the air. Sound waves are set up by any vibrating body, they travel through the air at a definite speed, and if their frequency and intensity are within certain ranges, they produce the sensation of hearing.

Sound Waves

If you touch the diaphragm of the loud speaker in your radio while it is playing, you can feel it vibrating. The diaphragm moves rapidly in and out on alternate sides of its neutral position. As it does so it carries with it the layer of air particles next to its surface. These air particles transmit their motion to the next layer, but because air is compressible and because it has weight, a small interval of time is required for the first layer to set the second layer in motion. The third layer is likewise set in motion by the second layer after a slight time lag. Each air particle duplicates the vibratory motion of the loud speaker diaphragm, but only after a time interval which is directly proportional to its distance from the diaphragm. This action constitutes a sound wave. The action of water waves produced by dropping a stone in a pond is quite analogous. The main difference is that water waves travel only along the surface and are therefore circular in shape, while sound waves, which spread out in all three dimensions, are spherical in shape. Furthermore, the motion of each water particle takes place both vertically and horizontally, as may be observed by watching a cork bobbing on a wave. In a sound wave each air particle vibrates only in the direction in which the wave is travelling, that is, along a straight line drawn between the particle and the source of the sound wave.

Velocity of Sound

All sound waves travel at a constant[1] speed of approximately 1120 feet per second, or 763 miles per hour. This speed is the same regardless of the pitch or loudness of the sound. The fact that sound takes time to travel explains why we hear a clap of thunder after we see the flash of lightning. The light travels almost instantaneously, but the sound does not reach our ears until after a time interval of about 5 seconds for each mile of distance from the lightning flash. The fact that sound does not travel instantaneously is also one of the most frequent causes of poor hearing conditions in auditoriums as will be discussed later.

Frequency

To return to the loud speaker diaphragm, we noted that it vibrated back and forth alternately about its center or neutral position. Each complete excursion or

[1]Actually, the speed varies slightly with the temperature. The velocity at 70° F. is approximately 1126 ft. per sec., and at 32° F., 1086 ft. per sec.

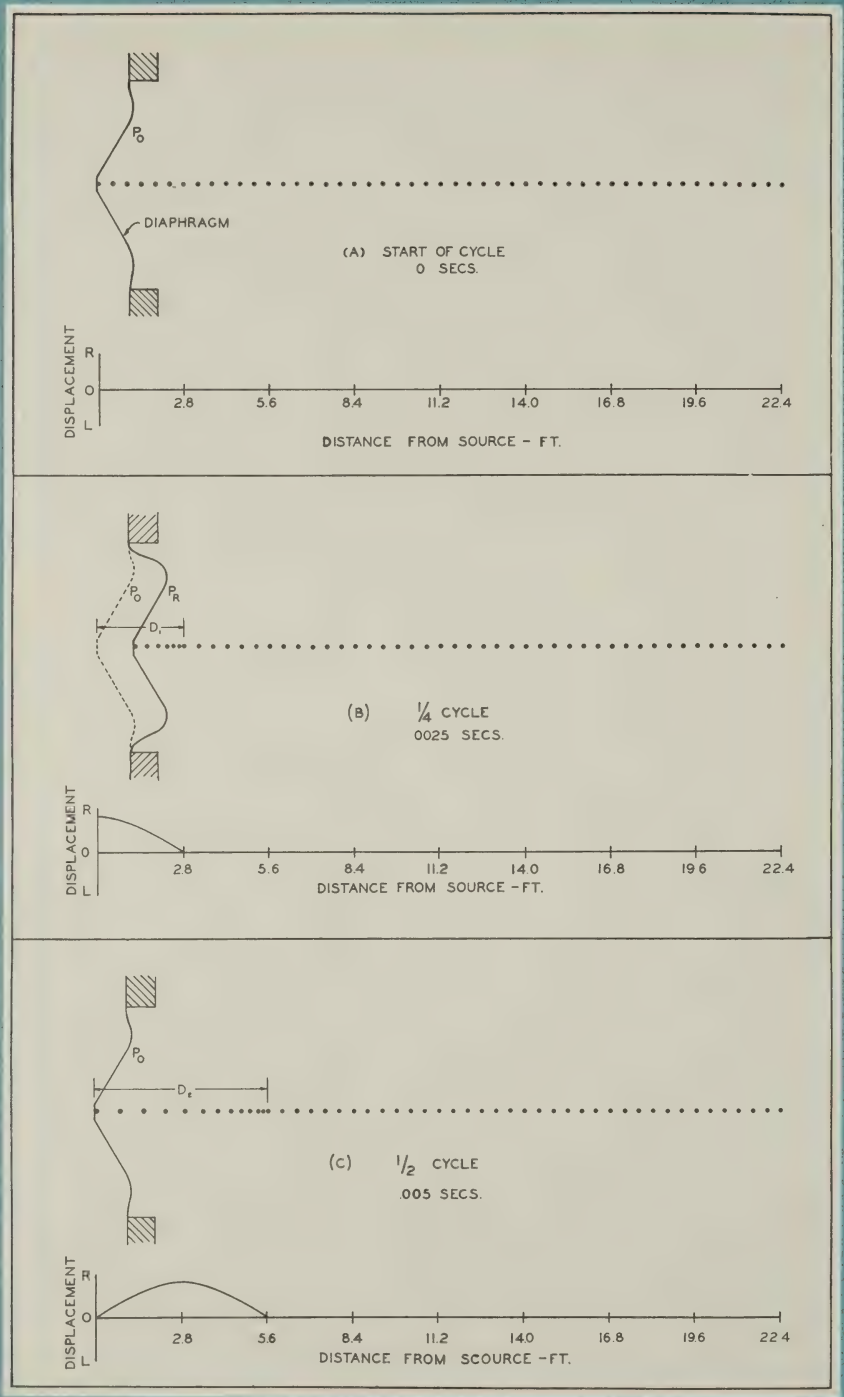


FIG. 1.1—*Propagation of sound waves by a vibrating diaphragm.*

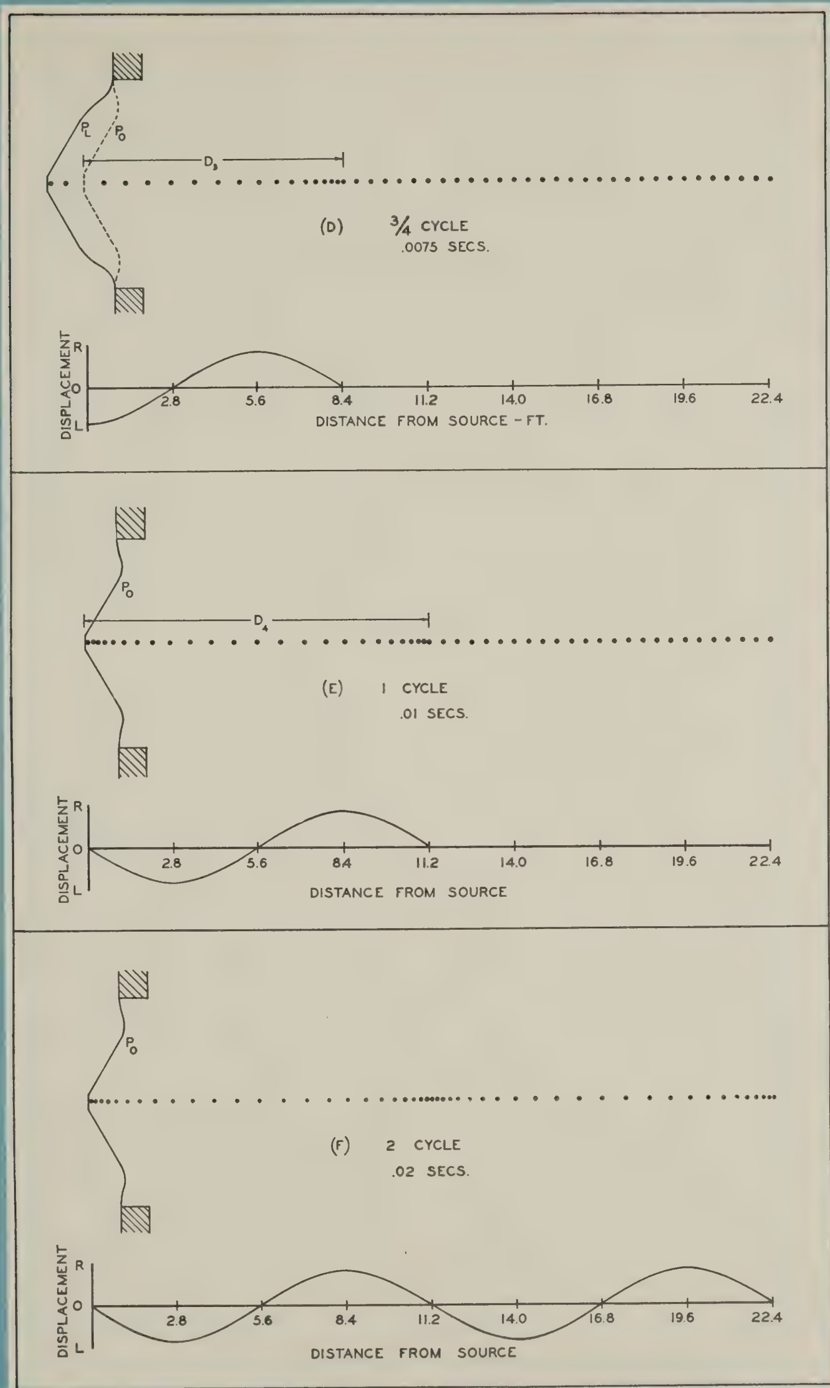


FIG. 1.1—*Propagation of sound waves by a vibrating diaphragm.*

"round trip" of any vibrating body, starting from its neutral position, moving to one side, then to the other side, and back to neutral, is called a *cycle*. The number of cycles performed in one second is termed the *frequency*. Since every air particle in a sound wave follows the motion of the vibrating sound source, each particle must necessarily have the same frequency as the source. For example, when we say that the sound from our loud speaker has a frequency of 1000 cycles, we mean that the loud speaker diaphragm and every particle through which the sound wave passes are vibrating back and forth 1000 times each second.

Wavelength

The wavelength of a sound wave may be defined as the distance the wave travels during each complete vibration or cycle of the sound source. Stated differently, the wavelength is, as the term implies, simply the length of each wave. It can be easily shown that the wavelength is equal to the velocity of sound (1120 ft. per sec.) divided by the frequency. Thus, a sound having a frequency of 100 cycles has a wavelength of 1120 divided by 100, or 11.2 feet. A 1000-cycle sound would have a wavelength of 1.12 feet.

From the discussion thus far we can now set up a picture of how a sound wave behaves, as in Figure 1.1. The loud speaker diaphragm vibrates back and forth between positions P_R and P_L to the right and left respectively of its neutral position P_O. (The extent of the motion is much exaggerated in order to show the action clearly.) The row of points represents a series of air particles along a single straight line extending out from the center of the diphragm. Figure 1.1-A is drawn just at the instant the diaphragm starts to vibrate. No sound has yet been emitted, and the diaphragm and the air particles are all in their neutral positions.

Let us assume that the diaphragm is set into vibration at a frequency of 100 cycles per second. A complete cycle would then take place in .01 second, and a quarter cycle, namely the motion from P_O to P_R, would require .0025 seconds. In Figure 1.1-B, a quarter cycle has been completed, and the front of the sound wave, travelling at 1120 feet per second, has reached the point D_1, which is 1120 x .0025, or 2.8 feet from the diaphragm. After half a cycle the diaphragm has returned to P_O and the wave has traveled to point D_2 which is 5.6 feet from the source, as shown in Figure 1.1-C. Figure 1.1-D shows the situation after three-quarters of a cycle, and Figure 1.1-E represents the completion of one cycle. The next cycle produces a similar wave which follows the one just described, as shown in Figure 1.1-F, and 100 successive waves will be sent out during each second that the diaphragm continues to vibrate. The distance from the source to point D_4 is the wavelength, 11.2 feet.

The graph under each diagram in Figure 1.1 shows the displacement of each air particle from its neutral position as related to the distance from the diaphragm. This is the conventional method of illustrating a wave graphically.

Intensity

The intensity[2] of a sound wave is a measure of the amount of energy contained in the vibrating air particles. The amount of energy, in turn, depends on the distance or *amplitude* over which the air particles travel on each side of their neutral position. The wider the amplitude of vibration, the greater is the intensity.

As our loud speaker diaphragm vibrates, it transforms the electrical energy supplied to it by the radio circuits into sound energy. This sound energy is emitted at a definite rate which is called the *acoustic power* of the source, and which is measured in watts, the same units with which we measure the rate of electrical power consumption of an electric iron or a light bulb. The sound energy travels outward from the diaphragm as fast as it is generated, in the form of sound waves.

Now imagine that a sound source which radiates sound energy equally in all directions is placed at the center of a sphere of, say, 100 centimeters radius. Sound energy is flowing outward through the entire surface of this sphere, and the total rate of energy flow through the spherical surface must be the same as the rate at which energy is supplied by the diaphragm, measured in watts. The rate of energy flow through each square centimeter of the spherical surface, or any surface at right angles to the direction of the energy flow, is defined as the sound intensity, and is measured in watts per square centimeter.

Now suppose we double the radius of our imaginary sphere. The surface of the sphere, being proportional to the square of the radius, will now be four times as great. The total energy flow across the larger spherical surface will remain the same, but it will be spread over the surface four times as thin. In other words, the energy flow across each square centimeter of the large

[2]In the interest of clarity for the non-technical reader, but at the expense of scientific accuracy, the term "intensity" will be used throughout this book to denote qualitatively or in comparative terms the strength of a sound field, generally at an observer's ear. Technically informed readers will recognize that in certain contexts, the terms "energy density", "pressure", or "pressure squared" should strictly be used.

sphere, or the sound intensity, will be one-fourth as great as for the small sphere. Thus, doubling the distance from the sound source reduces the sound intensity to one-fourth. Likewise, tripling the distance would reduce the intensity to one-ninth. This relation is known as the *inverse square law,* which states that the intensity is inversely proportional to the square of the distance from the source. The same law applies to the light intensity at various distances from a light source. The intensity also depends, of course, directly on the acoustic power of the source. If we double the electrical power supplied to our radio loud speaker by turning up the volume control, the acoustic power output of the speaker and the sound intensity at any point will likewise be doubled.

The actual sound intensity at any distance *d* centimeters from a nondirectional source of known sound energy output in watts is calculated by dividing the power of the source by the area in square centimeters of a sphere of *d* centimeters radius, namely, $4\pi d^2$.

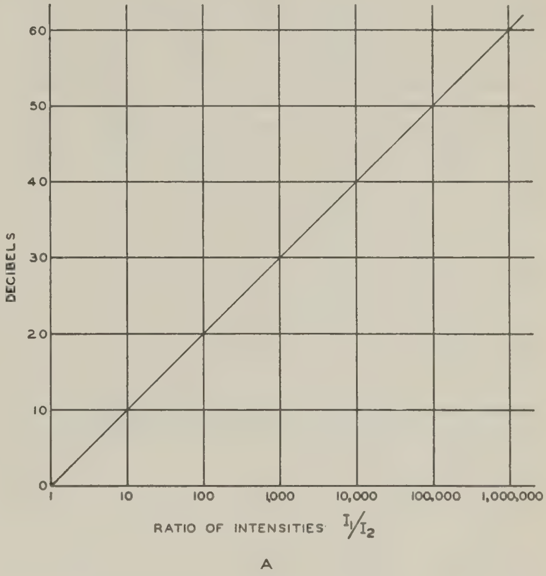
It should be pointed out here that the inverse square law determines the intensity of only the sound which travels in a direct line from the source to the point of observation. In a room, or in any location where sound reflecting surfaces or objects are in the vicinity, reflected sound waves will combine with the direct sound to produce a total intensity which depends on other factors. This will be discussed fully in later chapters.

Frequency Scale

In acoustical work frequencies are laid out in *octaves* in the same manner as a piano keyboard. The term "octave" is taken from musical terminology, and is defined as the interval between any two sounds having a frequency ratio of 2 to 1. The series of frequencies most commonly used in acoustical analyses and measurements are 128, 256, 512, 1024, 2048, and 4096 cycles. The frequency 256 cycles is approximately that of middle C on the piano, 128 cycles is the C an octave below, and 4096 cycles is four octaves above middle C, which is the top note of the piano. This series of frequencies covers most of the range of frequencies in speech and music.

Intensity Scale—Decibels

Measurements of hearing have shown that the normal ear is capable of receiving an incredibly large range of sound intensities. The loudest sound the ear can hear without a sensation of pain has about one trillion times the intensity of the faintest audible sound. In order to handle this tremendous range of intensities more conveniently in calculations, a unit termed *decibel* has been adopted (abbreviated "db."). The decibel is a unit for



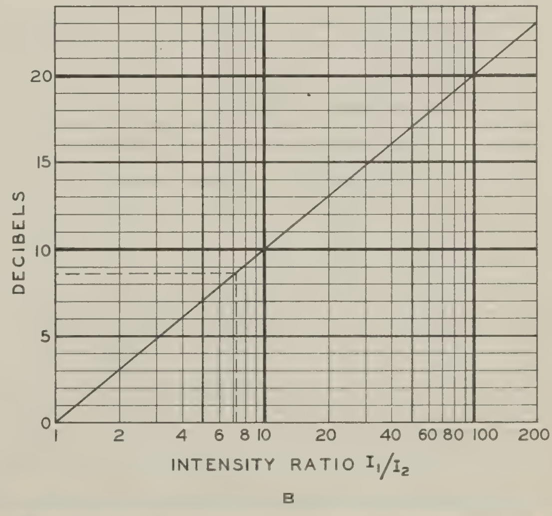


FIG. 1.2—*Relation of decibel scale to intensity ratios. Chart B is a magnification of lower left hand portion of Chart A.*

measuring the ratio of any two amounts of electrical or acoustic power. Sound intensity is really acoustic power, and therefore may also be measured with the same unit. The number of decibels denoting the ratio of any two sound intensities is defined as 10 times the logarithm[3] to the base 10 of that ratio. If I_1 and I_2 are two sound intensities, the number of decibels corresponding to their ratio is

$$N = 10 \log_{10} \frac{I_1}{I_2} \text{ decibels}$$

For example, if I_1 is 1000 times I_2, the logarithm of their ratio, 1000, is 3, and the number of decibels is 3 x 10, or 30; we say that the intensity I_1 is 30 db. above intensity I_2.

The relation of decibels to intensity ratios is shown in Figure 1.2. In Figure 1.2-a, the intensity ratio scale is carried only as far as 1,000,000, but it is evident that both the horizontal and vertical scales could be extended indefinitely, and that each 10-fold increase of the intensity ratio would give a corresponding addition of 10 decibels. Figure 1.2-b is simply a magnification of the lower left hand portion of the chart in Figure 1.2-a which shows intermediate values in greater detail. For example, suppose we wish to find the difference in decibels between two intensities having a ratio of 7.2 to 1. The dotted lines on Fig. 1.2-b show the answer to be 8.6 decibels. If the intensity ratio had been 72 to 1, the decibel value read from Fig. 1.2-b would be 18.6. It can be readily seen by reference to Fig. 1.2-a that intensity ratios of 720, 7,200, 72,000, etc., would have corresponding decibel values of 28.6, 38.6, 48.6, etc. By studying these charts, it will be seen, among other things, that doubling the intensity of any sound corresponds to an increase of approximately 3 decibels; also, that a one decibel increase corresponds to an increase in intensity of approximately 26 percent.

It has become standard practice in acoustical engineering to measure sound intensities in decibels, the term *intensity level* being used in conjunction with the decibel scale. (The common expression *noise level* refers to the intensity of noise when measured in decibels.) For example, we say that an office has a noise level of 80 db., or that a public address system produces a sound level of 70 db. in an auditorium. What we really mean is that the sound intensity we are measuring has a value such that its *ratio* to a second or "reference" intensity is denoted by 70 or 80 decibels, as the case may be. To say that a sound has an intensity level of 70 decibels without stating or implying the value of a reference intensity is as meaningless as to say that the population of a city is 30 percent, without stating whether it is 30 percent of the population of the county, the state, or another city. We must, therefore, establish the intensity corresponding to 0 decibels.

As a result of recent work in acoustical standardization, a reference sound intensity has been chosen for use with the decibel scale, and has been arbitrarily assigned a standard value of 10^{-16} watts per square centimeter. This amount of energy flow, one ten-quadrillionth of a watt, is extremely minute, but still large enough that a human ear a little more sensitive than normal can hear a sound of that intensity. This intensity then corresponds to 0 decibels, and the value of the reference intensity being understood, the statement of any intensity level in decibels definitely establishes the absolute sound intensity corresponding to that level. As an analogy, if we say that a mountain peak has an elevation of 5,000 feet, we know just how high it is only when we understand that 0 ft. is the elevation at sea level. Likewise, if we say that a sound has an intensity level of 60 db., we know that its intensity is 60 db. above an intensity of 10^{-16} watts per sq. cm., or that its intensity is 10^{-10} watts per sq. cm.

Figure 1.3 shows the intensity levels of common sounds on the decibel scale[4]. The *threshold of audibility* near the bottom of the scale is the intensity level of the faintest sound the ear can hear. The exact value varies somewhat between individuals, but the average for normal ears is a few decibels above zero. The *threshold of feeling* is the intensity level at which a sound is so loud as to begin to cause pain to the normal ear. The average value of this intensity level is approximately 120 db., which means that the intensity is about one trillion (1 followed by 12 zeros) times the intensity at 0 decibels.

Hearing

The frequency and intensity of a sound, which are purely physical characteristics, produce the correspond-

[3]The logarithm to the base 10 of a number is the number of times that 10 must be multiplied by itself to equal that number. For example, $100 = 10 \times 10 = 10^2$, therefore the logarithm to the base 10 of 100 is 2, or $\log_{10} 100 = 2$. Likewise, $\log_{10} 1000 = 3$, and $\log_{10} 10{,}000 = 4$. The logarithms of intermediate numbers are obtained from a slide rule or from published charts or tables.

[4]Taken from "Theory and Use of Architectural Acoustical Materials" published by the Acoustical Materials Association.

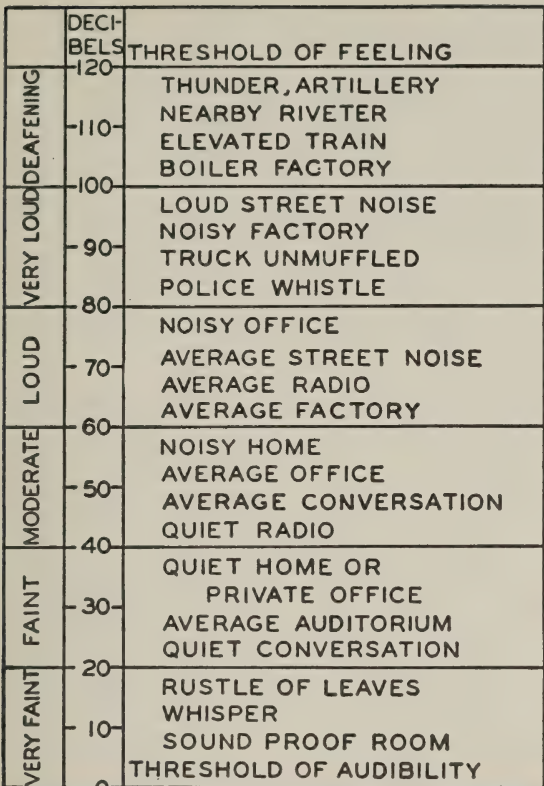


FIG. 1.3—*Decibel levels of common sounds.*

ing psychological sensations of pitch and loudness. High pitched sounds, such as whistles, squeaks, or treble notes of a voice or musical instrument, are high frequency sounds, and low pitched sounds, which we describe as rumbles, roars, or bass notes, are characterized by low frequencies. The loudness of a sound depends on its intensity; the greater the intensity, the louder is the sound.

The manner in which the ear responds to sound waves of different frequencies and intensities and converts them into sensations of hearing is quite complicated. Two sounds of the same intensity but of different frequencies do not necessarily sound equally loud, nor does one sound having twice the intensity of another sound appear twice as loud. A part of the story of how the ear does behave is given by the *equal loudness contours*[5] in Figure 1.4. The data shown by these curves has been obtained from a large number of carefully controlled experiments on the loudness judgments of persons with normal hearing.

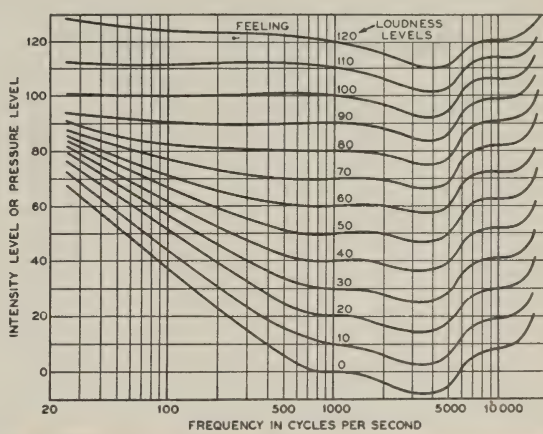


FIG. 1.4—*Equal loudness contours.*

The horizontal scale in Figure 1.4 indicates the frequency, and the vertical scale the intensity level in decibels. All points lying on one of the horizontal lines of the chart represent sounds which have the same intensity level, but different frequencies; all points along one of the vertical lines represent sounds of the same frequency, but having different intensity levels. The irregular curved lines are called "equal loudness contours." Each point on one of these contours represents a sound which appears to the average normal ear to be just as loud as the sound represented by every other point on the same contour. The figures along the vertical line at 1000 cycles, labeled "loudness levels," are for the purpose of identifying the positions of the various equal loudness contours. The *loudness level* of any sound is defined as the intensity level of a sound of 1000 cycles frequency which sounds equally loud. The unit of loudness level is termed the *phon*. Thus, for a frequency of 1000 cycles, the loudness level in phons of any sound of that frequency is equal to its intensity level in decibels, by definition.

To give a few examples, suppose a tone of 1000 cycles frequency were set so that it had an intensity level of 40 db. Now if the frequency were reduced to 100 cycles, the intensity level would have to be raised to about 62 db. in order for the tone to sound just as loud as before.

[5]Fletcher and Munson, J. Acous. Soc. Am., Vol. 5, p. 82, 1933.

(The 40 phon loudness level contour intersects the 100-cycle frequency line at an intensity level of about 62 db.) If the intensity level had been left unchanged at 40 db. as we lowered the frequency from 1000 to 100 cycles, the loudness level would have diminished from 40 phon to about 4 phon. (The 40 db. intensity level line intersects the 100-cycle frequency line at a point between the 0 phon and the 10 phon loudness level contours, namely at about 4 phon.) If the frequency had been reduced a little further, without changing the intensity level, the sound would have become inaudible, at about 88 cycles.

If the original sound of 1000-cycle frequency had been set at an intensity level of 100 db. instead of 40 db., the change in frequency from 1000 to 100 cycles would have produced no change in loudness. (The 100 phon loudness level contour practically coincides with the 100 db. intensity level line at all frequencies below 1000 cycles.)

As another example, at a frequency of 1000 cycles, there is a difference in intensity level of 40 db. between the 20 phon and the 60 phon loudness level contours. At 100 cycles, however, there is an intensity level difference of only about 20 db. between the same contours. In other words, it requires about twice the increase in intensity level to produce the same increase in loudness level at 1000 cycles as at 100 cycles.

From these examples, the following facts may be concluded:

(1) At low intensity levels, high frequency tones sound louder than low frequency tones of the same intensity.

(2) At high intensity levels, all tones of the same intensity sound almost equally loud, regardless of their frequency.

(3) At low intensity levels, a given change in intensity level produces a larger change in loudness at low frequencies than at high frequencies.

(4) At high intensity levels, a given change in intensity level produces practically the same change in loudness regardless of frequency.

These points will be referred to again in discussing reverberation-frequency characteristics.

The rest of the story of how the ear behaves has to do with judgment of the relative loudness of sounds. The average individual not only can tell which of two sounds is louder, but can assign a percentage relationship to the two sensations of loudness with a fair degree of certainty, as when he estimates that one sound is one-third, one-half, or two-thirds as loud as a second sound. The problem has been to relate these loudness judgments to the intensities of the sounds. As has been said before, the ear estimates loudness neither in proportion to the intensity, nor according to the intensity level. If we decrease the intensity by one-half, the ear will judge that the loudness is decreased by less than one-half. However, if we decrease the intensity level from, say, 60 to 30 db., the ear will estimate a loudness reduction of considerably more than one half.

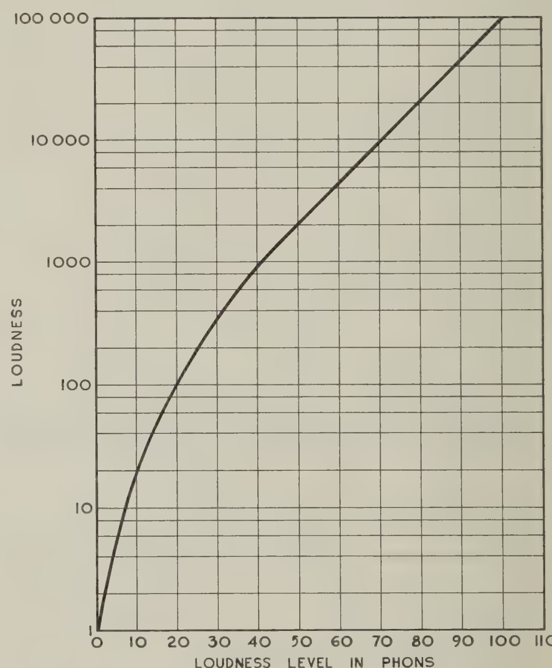


FIG. 1.5—*Curve showing relation of loudness to loudness level.*

As a result of extensive listening tests on groups of trained observers, it has been found that the average individual's estimate of the relative loudness of any two sounds can be related directly to the loudness levels of the sounds in phons. This relation is shown in Figure 1.5, which is based both on averaged experi-

mental data and on theoretical considerations.[6] The vertical scale, labelled *loudness*, is laid out in units for which no name has as yet been adopted, but which are directly proportional to the magnitude of the loudness sensation. For instance, a sound of 60 phon loudness level has a loudness of 4600. By reducing the loudness level from 60 to 50 phon, a 10 phon reduction, we decrease the loudness to 2130, which means that the average listener would estimate that the sound is a little less than half as loud as before. Reducing the loudness level another 10 phons would bring the loudness down to 990, and the observer would estimate that the loudness was again cut in half. Below 40 phons, a given reduction of loudness level produces increasingly larger percentage loudness reductions as the initial level approaches inaudibility. In Figure 1.6, the same data as in Figure 1.5

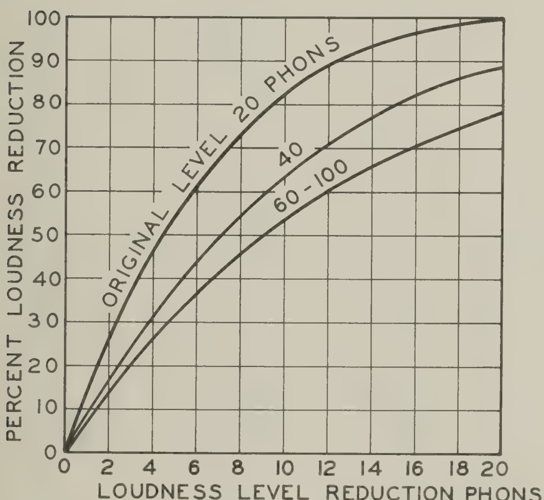


FIG. 1.6—*Curves showing percentage reduction of loudness as a function of the reduction in loudness level, for various original loudness levels.*

is plotted so as to show percentage reductions in loudness corresponding to reductions in loudness level in phons, for various original levels.

[6]Harvey Fletcher, J. Acous. Soc. Am., Vol. IX, p. 275, 1938. This curve and the ones in Fig. 1.6 differ slightly from those shown in the previous edition of *Less Noise . . . Better Hearing*. Although the latter have been recommended as standard by the American Standards Association, the ones published here are considered preferable because they are based on later and more complete data and are of somewhat simpler form.

By referring back to the loudness level contours in Figure 1.4, it will be seen that changes in loudness level are practically equal to changes in intensity level over most of the frequency range. Therefore, for most practical cases, intensity level reductions may be used instead of loudness level reductions in estimating loudness changes from the charts in Figures 1.5 and 1.6. This is a convenient substitution, since most of the formulae and calculations in acoustical work are based on intensity levels rather than loudness levels. It should be noted, however, that for sounds having a frequency of less than about 100 cycles, this substitution is not valid.

One other fact of interest has been discovered in experiments on hearing, namely that for the intensities and frequencies of sound normally encountered, the least difference in loudness that the average ear can detect under the most favorable conditions is equal to about one decibel.

Speech, Music, and Noise

One characteristic of sound which has not yet been discussed is that it may have, and usually does have, several different frequencies at the same time. This means that the source of the sound must also be vibrating at several different frequencies simultaneously. That this is possible may be demonstrated quite simply. Hold your pencil vertically between your thumb and finger by one end, and rotate your wrist so that the other end of the pencil moves rapidly back and forth at a frequency which we will call *A*. Now hold the pencil still and move your whole arm back and forth slowly. The pencil point will now be vibrating at a lower frequency, *B*. Now combine both motions, wiggling the pencil rapidly as you move your arm slowly. The pencil point will now be vibrating at two frequencies *A* and *B* at the same time. If you could somehow speed up the motion enough to produce an audible sound wave, each air particle in the wave would be vibrating at both frequencies, and your ear would hear two tones together. A sound having only a single frequency is called a *pure tone*, and a sound which contains two or more frequencies simultaneously is called a *complex tone*.

Practically all sounds that we hear every day are made up of a number of different frequencies. When a musical instrument is played, the string, the reed, or the

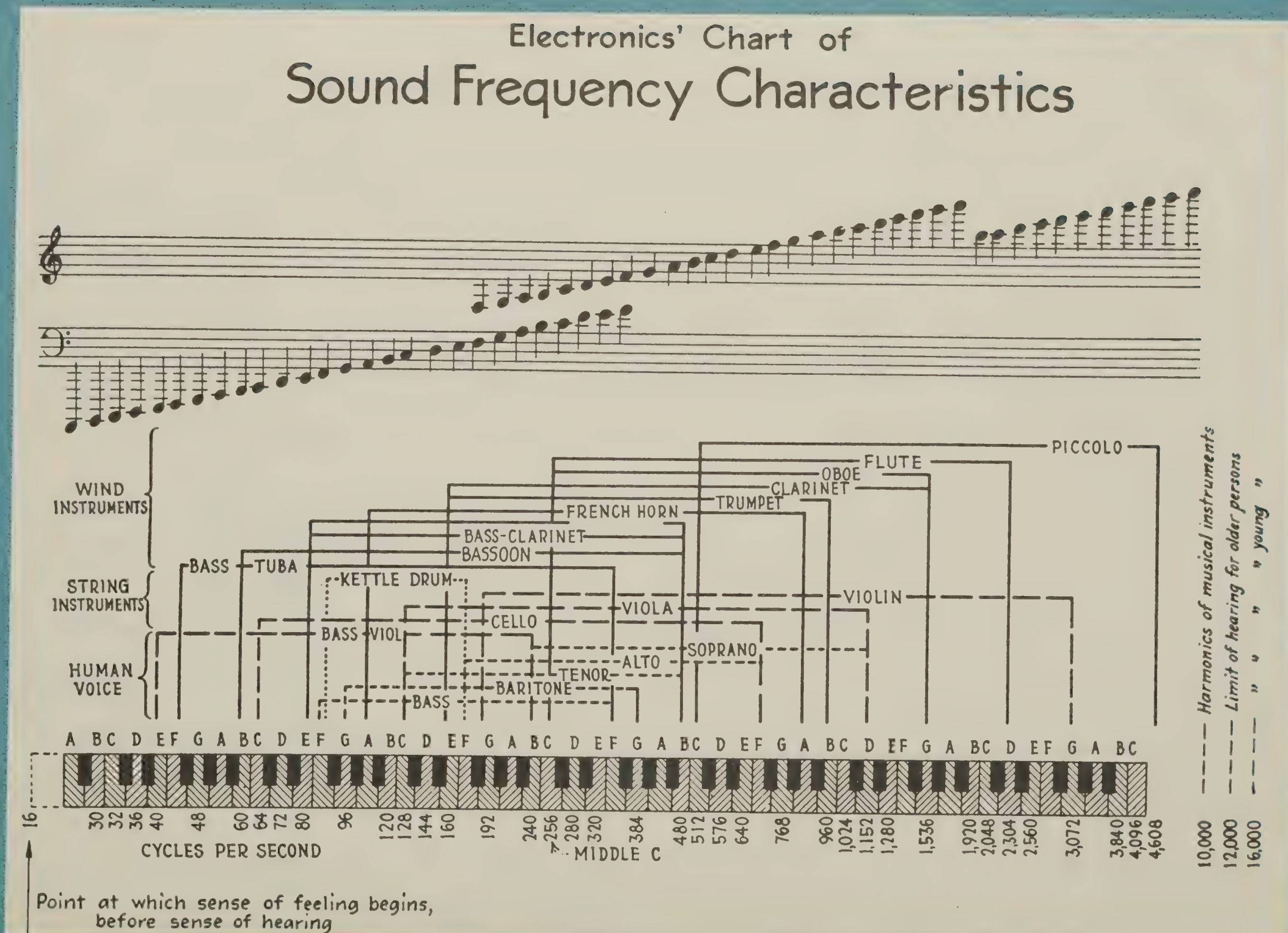


FIG. 1.7—*Frequency ranges of various sounds and sound reproducing devices.*

lips of the player, as the case may be, vibrates at a number of different frequencies simultaneously. The lowest frequency is called the *fundamental,* and it is this frequency which the ear singles out and identifies as the pitch of the note being played. All of the other frequencies are called *overtones* or *harmonics.* Ordinarily we do not hear the overtones as individual notes, but instead we perceive all of them together and interpret the whole group of overtones as the *quality* of the sound. Differences in the number and intensity of the overtones are heard as differences in quality between various sounds, and it is chiefly the quality of a sound that enables us to recognize it and distinguish it from other sounds. For example, if we listened to the same note played with the same loudness first on a violin and then on a flute, we could easily distinguish between the two instruments because they differ widely in their characteristic overtone distribution.

The understanding of speech likewise depends on the ability of the ear to distinguish between different tone qualities. Each vowel sound has a characteristic set of overtones whose frequencies are determined by the shape of the mouth cavities, these overtone frequencies ranging from 200 to 3,000 cycles for the various vowels. Consonant sounds, such as "s" and "sh," may contain frequencies as high as 10,000 cycles. The understanding of speech consists of hearing the various overtones and interpreting them as vowel and consonant qualities.

Speech sounds also contain a fundamental pitch, which is produced by the vocal cords and whose frequency depends on the individual and his manner of speaking. The fundamental frequency of men's voices in normal conversation averages around 125 cycles, and of women's voices, 250 cycles. It is not necessary to hear this fundamental frequency in order to understand speech; only the vowel and consonant overtones are required. In whispering, for example, the vocal cords are not used at all, and no fundamental frequency is present. A telephone transmits the fundamental voice frequencies very inefficiently as compared with the vowel and consonant frequencies, but this attenuation of the low frequencies affects only the naturalness and not the intelligibility of the transmitted speech.

Figure 1.7 illustrates the ranges of frequencies of various types of sounds dealt with in architectural acoustics.[7] It can be seen that frequencies covering nearly the entire audible range are commonly present, and that in the transmission of sound, either acoustically through the air in a room or electrically through microphones and loudspeakers, the naturalness and intelligibility of each sound must be assured by preserving as faithfully as possible the characteristic frequency components which it contains.

Noise is best defined as unwanted sound. Noise may be musical in character, as of an automobile horn or a neighbor practicing his trombone at midnight, but more often it is of an irregular, non-musical, and distinctly disagreeable quality, as of office or restaurant noise or of street traffic. Noise of this type seldom has any one predominant frequency that may be distinguished by the ear or detected instrumentally, but instead usually contains an extremely large number of frequency components spread over a wide frequency range.

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[7]Reproduced by permission from *Electronics* magazine, McGraw-Publishing Co. Inc., New York.

Seminary of St. Thomas Chapel, Denver, Colorado. Acoustical conditions favorable to services held here are provided by the Acousti-Celotex tile ceiling. Note rich designs applied directly to the tile. Architect, J. B. Benedict.

Chapter II

Sound Absorbing Materials

WHEN A SOUND WAVE strikes a wall, or any material surface, part of its energy will be absorbed and the remainder of the energy will be reflected. The percentage of the energy absorbed by a material when a sound wave is reflected from it is called the *sound absorption coefficient* (also termed *acoustic absorptivity*) of that material, and may vary from 1 or 2 per cent to nearly 100 per cent for various materials. The absorption coefficient of a material depends on the nature of the material itself, on the frequency of the sound, and on the angle at which the sound wave strikes the surface of the material.

A large part of architectural acoustics deals with the improvement of hearing conditions and the abatement of noise in rooms by reducing the energy of reflected sound. This is accomplished by finishing the interior surfaces of rooms with *acoustical materials,* that is, materials which have substantially higher absorption coefficients than the conventional finish materials such as hard plaster, wood, concrete, glass, etc. Postponing for the moment the analysis of acoustical problems, this chapter will discuss the properties and characteristics of acoustical materials.

Rating of Absorption of Materials

As stated above, the absorption coefficient of every material varies with the frequency of the sound. It is common practice, therefore, to list the coefficients of a material at the six frequencies, 128, 256, 512, 1024, 2048, and 4096 cycles. Some testing laboratories measure and publish coefficients for frequencies above and below this range. In using a single coefficient for comparing materials considered for the improvement of hearing conditions in an auditorium, the coefficient at the frequency 512 cycles has been selected. In comparing materials for noise quieting applications, the *noise reduction coefficient* is used. This is the average, to the nearest multiple of .05, of the coefficients at the four frequencies 256, 512, 1024, and 2048 cycles.

It was also mentioned above that the coefficient of a material varies with the angle at which the sound strikes its surface. The published value for each frequency is really the average of the coefficients for all the angles at which the sound wave can possibly strike the surface. This averaging process is automatically taken care of in the method of measurement.

Absorption by Porosity

Practically all sound absorbing materials owe their efficiency to the fact that they are highly porous. In absorption of this type, the air inside the pores of the material is set into vibratory motion by the incident sound waves, and the friction of this motion against the walls of the pores generates heat. A fraction of the total energy of the incident sound wave, namely the absorption coefficient, is thus transformed into heat energy,

and the remaining fraction of the sound energy is sent back into the room as a reflected sound wave.

The absorption coefficient of a porous material depends in a rather complicated manner on the thickness, the size of the pores, the ratio of pore volume to total volume, and the frequency of the sound. Although it is quite difficult to evaluate all of these factors with a view to predicting the absorption of a material, several approximate statements may be made. In the first place, in order for the pores of a material to absorb sound effectively, they must communicate with each other and with the surface of the material. Second, the absorption increases with the thickness, particularly at low frequencies. At high frequencies, for some materials, an increase in thickness has little or no effect on the absorption. Third, the absorption increases, up to a certain point, with the degree of porosity, as measured by the rate at which air can be forced through it. For a given type of material, the lower the density, the more porous it is. If the size of the pores is increased beyond a certain point, however, so as to produce an extremely loose textured material, the absorption decreases. Fourth, the absorption of practically all materials is greater for high frequencies than for low frequencies. The extent of variation depends mainly on the thickness, being greatest for thin materials. Some materials may show a maximum absorption at 512 or 1024 cycles, with decreasing absorption at higher frequencies.

Effect of Furred Mounting

When a material is mounted on furring strips with an air space behind it, its absorption at the low frequencies is increased. This may take place in one or both of two ways, depending on the nature of the material. If it is of a board or panel type, it is more or less free to vibrate flexurally under the action of incident sound waves. Internal friction in the body of the material is set up by this bending motion, and part of the sound energy is transformed into heat energy in overcoming this friction. Thus sound is absorbed by the vibration of the material as a whole, rather than by porosity. The amount of absorption depends on the extent of vibration possible, which in turn requires that the material be comparatively light and flexible.

If the back surface of the material is not impervious to sound, the low frequency absorption will increase because the air space in effect increases the thickness of the material. The greater the total distance from the face of the material to the solid backing behind the air space, the larger will be the increase in low frequency absorption, and the lower will be the frequencies at which substantial increases occur. This effect may be frequently accompanied by a drop in absorption at the middle frequencies.

Effect of Perforations

During some early experiments on the use of Celotex cane fibre board as an acoustical material, the idea was conceived that the absorption of the material could be increased by drilling a number of deep holes into the surface so as to increase the area of material exposed to sound waves. An increase in absorption was found, but it was much greater than could be accounted for by the effective increase in area. Another surprising discovery was that the application of paint to the surface of the perforated board caused no measurable reduction in absorption. Various types of paint application were tried, some of them heavy enough to destroy almost entirely the absorption of the unperforated board, but in no case did the application of paint affect the absorption of the perforated board.

Experiments on other products showed that covering the surface of a porous material with a thin perforated screen of metal or other non-porous material did not reduce the absorption in the same ratio as the surface area covered, but instead at most frequencies the absorption remained the same or even increased substantially. At the high frequencies the absorption was reduced to some extent, but still not in direct proportion to the percentage of area covered.

These effects can be explained for the most part by the phenomenon of *diffraction*, which is the tendency of sound waves to flow readily around obstacles which are small in comparison to the wavelength of the sound. The non-porous spaces between the perforations may be considered as small obstacles around which the sound waves flow practically unimpeded into the perforations, where the absorption takes place.

Effect of Paint

In order for a porous material to absorb sound, the sound waves must have access to the porous interior of the material. The reduction in absorption of a material due to painting the surface will depend, therefore, on the extent to which this access is destroyed. In materials of the insulating board type, that is, homogeneous materials composed of fine vegetable or mineral fibre and having a comparatively smooth, unbroken surface, access to the interior is attained entirely by surface

porosity. Any paint coating which forms a hard, continuous film over the surface will seal up the pores which communicate with the surface and will almost entirely destroy the absorption of the material. If, however, paint can be applied in such a manner as to color the individual fibres without filling up the pores between the fibres, the original absorption can be preserved.

This latter requirement, however, is difficult of attainment in practice, especially where high light reflection is desired. All oil or water paints contain a certain percentage of solid pigment. If these paints are applied in such a manner as to obtain satisfactory hiding, the surface porosity will inevitably be affected by the film of pigment which is deposited. If a very light coat of paint is applied, the porosity may be preserved, but the hiding will probably be inadequate and the finished appearance unsatisfactory. Dyes and stains, which soak into the surface without filling the pores, may be used, although it is difficult to increase the light reflection of the surface by this means.

The fibre board type of material described above is the least paintable type of acoustical material. At the other extreme, as regards paintability, is the mechanically perforated type of material such as Acousti-Celotex Cane or Mineral Tile. In this case, as was explained above, the absorption takes place in the perforations, so that the surface may be covered with any kind of paint coating provided the perforations are not covered over. Repeated laboratory tests on Acousti-Celotex Cane and Mineral Tile have definitely established the fact that these materials can be painted repeatedly with any kind of paint without reducing their absorption. The restriction against closing any of the holes with paint is easily met in practice, because the perforations are large enough that it would actually be a difficult matter to cover them with paint of easy brushing consistency. With perforated materials having smaller holes than those in Acousti-Celotex Cane or Mineral Tile, it is necessary to use care in order to avoid covering the holes with paint.

Complete and unqualified paintability of an acoustical material is obviously a very important requirement for installations such as offices, schools, and hospitals, where high light reflection and frequent maintenance are needed. Such a material presents no new maintenance problems, because the standard procedure of cleaning the painted surface or repainting at the customary intervals may be followed.

Between these two extremes of paintability are ranged other types of acoustical materials having partial paintability to a greater or less extent. These include acoustical plasters, materials with coarse surface porosity, and materials having large fissures in the surface which act in much the same manner as perforations.

Types of Acoustical Materials

As of today, practically all products listed and used as acoustical materials can be classified in three groups. In the order of use, they are, (1) Prefabricated Tiles, (2) Assembled Units, and (3) Plastic Compositions.

The prefabricated tiles are by far the most widely used. For general application, this type has a number of advantages. Through adequate control of density, thickness, dimensions and finishes during the manufacturing process, tiles with uniform absorption characteristics and matching appearances can be produced in large quantities. Absorption capacities and characteristics are inherent in the tiles. Due to this possible precision in manufacture, their performance after installation can be relied upon to match that indicated by the standard test data on which they are rated.

Assembled units include the various combinations of sound absorbing elements such as rockwool and glasswool blankets, pads or other sound absorbing materials, with acoustically transparent facings. These combinations are used primarily in broadcasting and recording studios, special music rooms, etc. where some controlled variation of sound absorption characteristics may be desirable. They are also used in some instances for general sound conditioning where the greatest possible sound absorbing capacity may be required. By varying the thickness of the sound absorbing element and the spacings between the element, the wall and the facing, some variation in the over-all absorption and the absorption at different frequencies can be obtained. In practically all instances today the facings used are some form of a durable perforated panel such as asbestos board, hardboard or metal. The original use of cloth, usually muslin, has been discontinued because of difficulties and expense in maintenance.

Celotex Acousteel, while properly an assembled unit type, is used as a prefabricated tile where a high absorption capacity is required. The parts of this material are prefabricated to established specifications and are usually assembled on all installations with a standard relationship between the parts.

Plastic compositions include the acoustical plasters and the various kinds of "sprayed-on" materials. The plasters are built up on the wall and ceiling surfaces in the usual way. The sprayed-on types are applied by special guns. These materials are characterized by their smooth, unbroken surfaces. Their limitations lie in the indeterminate absorption characteristics and maintenance. With this type, absorption depends critically on proper application, and due to their fine surface porosity, paintability is narrowly restricted.

For its quieting effect, Acousti-Celotex tile was applied to the ceiling in the waiting room of Ellis Hospital, Schenectady, New York. Architects, Heacock, Hokanson and Scheuringer.

Chapter III

Sound Waves in a Room

In order to understand how acoustical materials reduce noise and improve hearing conditions, it is necessary first to form a picture of what happens to sound waves and the energy they contain when sound is generated in a closed room. It will be attempted in this chapter to present such a picture descriptively.

Reflection of Sound

When a sound source is in operation, sound waves travel outward in all directions radially from the source. When the sound waves encounter an obstacle or surface, such as a wall, their direction of travel is changed; in other words, they are *reflected.* Figure 3.1 illustrates the reflection of waves originating at the sound source *S* from a plane wall, *W*. The curved black lines represent a train of waves spreading outward in the directions indicated by the black arrows. The curved blue lines and blue arrows illustrate the behavior of the waves after they have been reflected by the wall. From an inspection of this figure it will be seen at once that the reflection of sound follows the same laws as the reflection of light from a plane mirror. Two facts are apparent: (1) the direction of travel of the reflected sound always makes the same angle with the wall as that of the incident sound; (2) the reflected sound waves travel exactly in the same manner as they would if they had originated at the "image" of the sound source, *S′*.

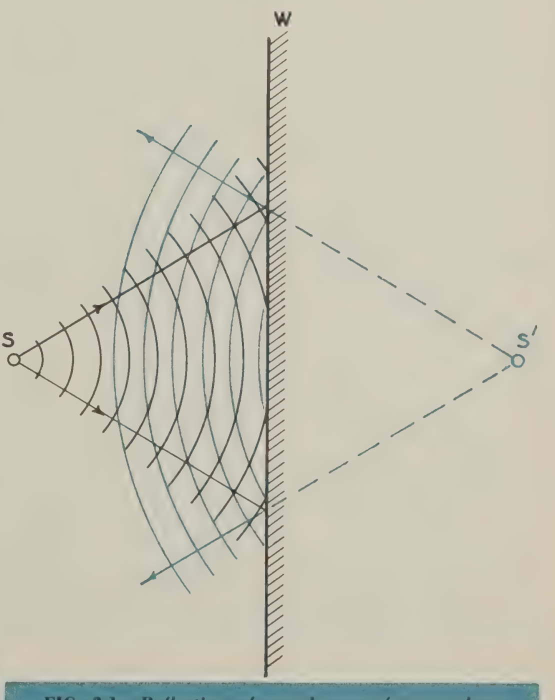


FIG. 3.1—*Reflection of sound waves from a plane surface.*

This image source is located the same distance behind the wall as the real source in front of the wall, just as in the case of a light image in an ordinary mirror.

Knowing these two facts, it is not difficult to set up a sort of motion picture of the progress of a sound wave in a closed room. The diagrams in Figure 3.2 represent a horizontal section of a room 24 ft. by 40 ft., with plane, sound reflecting walls, and with a sound source located at S. The black circle in Figure 3.2-A represents the "front" of a single sound wave, and the blue arrowed lines indicate the directions in which it is travelling. Figure 3.2-A was "snapped" 1/200th of a second after the front of the wave had left the source S, and shows that no reflections from the walls have yet taken place. Figure 3.2-B is taken 1/100th second after the start of the wave. The wave front has now travelled twice as far as in the first figure, and part of it is being reflected from the nearest end wall. In Figure 3.2-C, taken after a total time interval of 1/50th second, reflections from the side walls, and also double reflections from the end and side walls, are taking place, as shown by the blue arrows. In Figure 3.2-D, taken at about 1/17th second after the start of the wave, the reflection pattern is quite complicated. The original wave front, which started out as a circle, is now broken up into a large number of segments, all travelling in different directions through the room. In addition to the segments shown in Figure 3.2, there would also be segments of the original wave front which had been reflected by the floor and ceiling, but which cannot be shown on a horizontal section.

It is seen that almost immediately every part of the room is filled with reflected sound waves travelling in every possible direction. There are two effects of this multiple reflection which have a direct bearing on architectural acoustics.

Effects of Multiple Reflection

The first effect is the increase in sound intensity caused by reflections. Every one who has driven his car through a subway has noticed that the noise of the car is louder than on the open road, due to reflection from the walls and roof of the subway. Referring again to Figure 3.2, it will be seen how this same effect takes place in a room. If a continuous sound is made, a listener in any part of the room will receive not only the sound waves which come directly to his ear from the

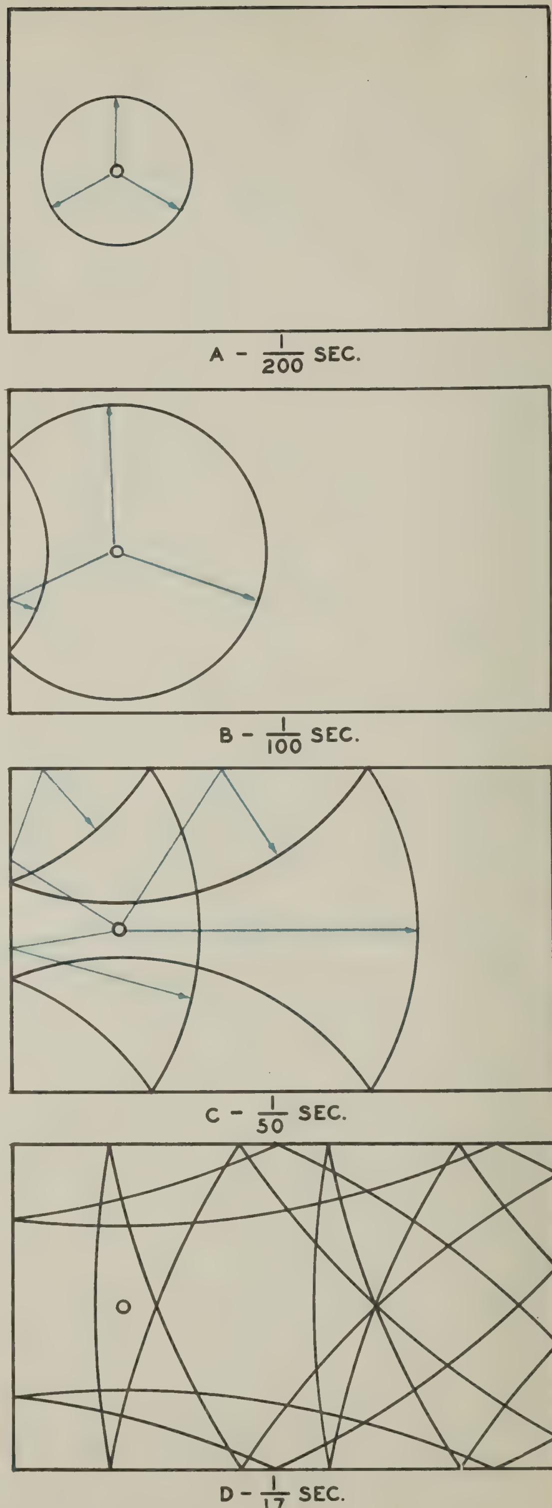


FIG. 3.2—*Multiple reflection of a single wave front in a closed room.*

sound source, but will hear also all of the reflected waves. Thus the combined loudness of the direct and reflected sound will be greater than that of the direct sound alone. The total loudness will depend on the amount by which the energy of the reflected waves is reduced at each reflection, or in other words, on the absorption coefficient of the room surfaces.

If the absorption coefficient of the interior surfaces is low, as in a room finished entirely in hard plaster, concrete and glass, which have coefficients of less than 5 percent, the reflected sound waves will lose very little energy at each reflection and will build up the total loudness to a level far above that of the direct sound alone.

The second effect of multiple reflections is reverberation. Looking at Figure 3.2 once more, we see that while the sound source is operating, the room becomes filled with reflected sound waves. If the source is stopped at any given moment, these reflected waves will not simply cease to exist at that moment, but instead will continue to travel back and forth between the room surfaces. At each successive reflection thereafter, each wave will lose a fraction of its energy by absorption, and the total sound energy in the room will gradually diminish. If a listener is in the room, the reflected waves strike his ear in such rapid succession that he usually does not hear them as distinct repetitions of the original sound. Instead, he hears the original sound being drawn out or prolonged after the source is stopped, and steadily dying out until it becomes inaudible. This prolongation of sound is called *reverberation.*

If all the interior surfaces of a room are of materials with low absorption coefficients, such as plaster, concrete, or glass, each sound wave will lose very little energy at each reflection, and the total sound energy in the room will decrease at a slow rate.

These two effects of multiple reflection are illustrated in Figure 3.3. The loudness is that heard by an observer situated at any arbitrary point in the room assumed to be far enough away from the sound source that the total sound energy at his ear is due almost entirely to reflected rather than directly transmitted waves. The solid line, drawn for the case of highly reflective interior surfaces, shows the loudness building up to a high value immediately after the source is started and dying out slowly as reverberation after the source is stopped. The dotted lines show the effects of increasing the average absorption coefficient of the room surfaces in differing degrees by means of acoustical materials. Reducing the intensity of reflected sound waves by absorption has the two basic effects of (1) lowering the level to which the loudness builds up while the source is sounding, and (2) increasing the rate at which the reverberant sound dies out after the source is stopped.

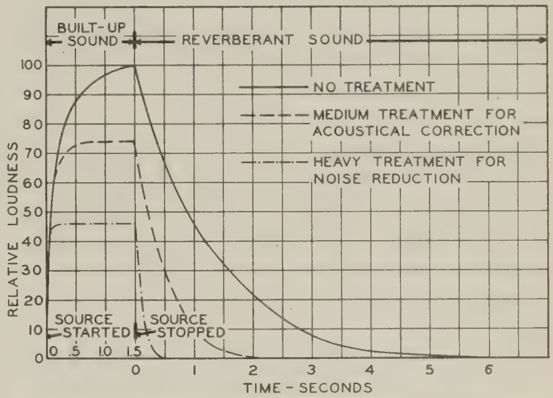


FIG. 3.3—***Chart showing building up and dying out of sound in a room with varying absorption.***

Acoustical Correction and Noise Reduction

While both of these effects always occur together in any room in which absorbent material is introduced, the use of acoustical treatment is customarily referred to as being for the purpose either of *acoustical correction,* that is, the attainment of the best possible hearing conditions for wanted sound in auditoriums, music rooms, etc., or for *noise reduction,* which means the alleviation of the discomfort and distraction caused by the reflection of unwanted sound. There are certain conditions, of course, such as in grade school class rooms, gymnasiums, etc., where both functions of acoustical treatment are equally desirable.

The long persistence of sound in a highly reflective room is termed *excessive reverberation,* and in nearly every case is the principal cause of poor hearing conditions in auditoriums, theatres, and other audience rooms. Excessive reverberation is particularly disastrous to the clear understanding of speech. If at the moment a speaker is uttering one syllable the sound of the preceding three or four syllables is still audible in the room with nearly their original loudness, it is easy to see that the resulting overlapping and confusion of successive words and syllables causes extreme difficulty in understanding speech. The best example of this is the familiar experience of trying to understand train announcements

called out in a large, bare station waiting room. In listening to music under extremely reverberant conditions, the blurring and lack of definition of successive notes produces a very unpleasant effect similar to that of playing a piano with the loud pedal held down continuously.

Acoustical correction of auditoriums consists of the application of acoustical material in a large enough quantity and having a high enough absorption coefficient that the rate at which the reverberant sound dies out is increased to within the proper limits. The result is a clarity and distinctness of successive elements of speech and music which insures easy, effortless hearing such as one experiences in his own living room.

When the treatment is used for acoustical correction alone, as in an auditorium, the amount of absorption introduced should be only enough to control the reverberation satisfactorily. Amounts greatly in excess of this requirement are not only uneconomical but may impart an unnaturally "dead" quality to the wanted sound.

The annoyance and confusion due to excessive reflection of unwanted sound, or noise, is due both to the magnification of the original sounds to unnecessarily high intensities and to their prolongation by reverberation. There is evidence also that much of the distracting quality of noise in a highly reflective room arises from the fact that most of the sound energy created by a given noise source strikes the ear from many directions other than that of the source itself. Since all the effects of reflection are undesirable where noise is concerned, the logical objective in the use of acoustical treatment for noise reduction is to remove as much reflected sound as possible. In practice, considerably larger amounts of absorption are used for alleviating noisy conditions in a given room used as a work space than would be necessary or desirable simply for acoustical correction of the same room used as an auditorium. The relative effects of typical treatments designed for these two purposes on the built-up loudness and on the reverberation are shown in Figure 3.3.

From the standpoint of comfort there is little danger in introducing too much absorption when used strictly for purposes of noise reduction. The theoretical limit to the effect of absorbent treatment is, of course, the complete elimination of reflected sound accomplished by making all interior surfaces 100 percent absorptive. In this case, the only sound heard in the room would be that which travelled directly from the source, its loudness being governed only by the observer's distance. To the ear, this would be exactly equivalent to the physical removal of the walls and ceiling of the room, or the transferrence of the source and listener to the outdoors. The provision of this much absorption is generally impractical structurally and economically, except in very special cases, and somewhat smaller amounts, adjusted to the size and shape of the room and the intensity and distribution of noise sources in it, have been found in practice to insure entirely satisfactory control of reflected sound.

Chapter IV

Acoustics of Auditoriums

An acoustically satisfactory auditorium is one in which every member of the audience can hear and understand speech distinctly and without effort, and in which the sound of music is transmitted throughout the room with a natural and pleasing quality. In order for good hearing conditions to be assured, four requirements must be met:

1. The room must be free from excessive reverberation at all frequencies.
2. The sound must be sufficiently loud in every part of the room.
3. There must be no interference due to echoes.
4. There must be no disturbance caused by extraneous noise.

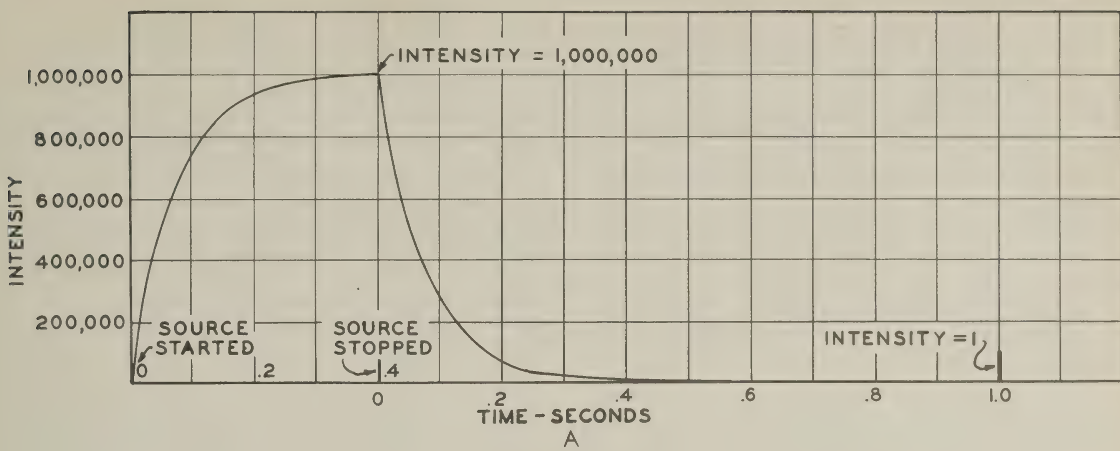
REVERBERATION

Building up and Decay of Sound Intensity

When a sound source is started, the sound intensity at each point in the room builds up rapidly, due to the accumulation of reflected waves, and quickly reaches a steady value which does not change as long as the source continues. This *steady state* intensity is not the same everywhere in the room, but fluctuates from point to point. This variation is due to the phenomenon of *interference,* which may be described as follows. If two similar waves are travelling in opposite directions in such a manner as to "pass through" each other, it can be shown that along the line of travel of the waves there will be a series of fixed points, all spaced one-half wavelength apart, where the motion of the two waves will be exactly in phase, at which points the amplitude of vibration of the air particles will be just twice the amplitude that would be produced by either wave alone. There will also be a series of intermediate points where the two waves will be completely out of phase and will cancel each other, resulting in zero amplitude of vibration. This alternate doubling and cancellation of amplitude from point to point is called interference, and in the elementary case just described the *interference pattern* is quite simple.

When a sound source is operating in a closed room, however, there are hundreds of reflected waves, all having different amplitudes and travelling in different directions, which may pass through any given point. The interaction of all these waves therefore produces an exceedingly complex interference pattern. The effects of interference are very noticeable to the ear if the observer closes one ear and listens to a steady, high pitched tone. By moving the head only a few inches, the loudness can be heard to fluctuate widely, and some

Sound Conditioning with Acousti-Celotex tile creates a comfortable environment for ballroom functions in Coffman Memorial Union Building, University of Minnesota. Architects, Office of Clarence H. Johnson.



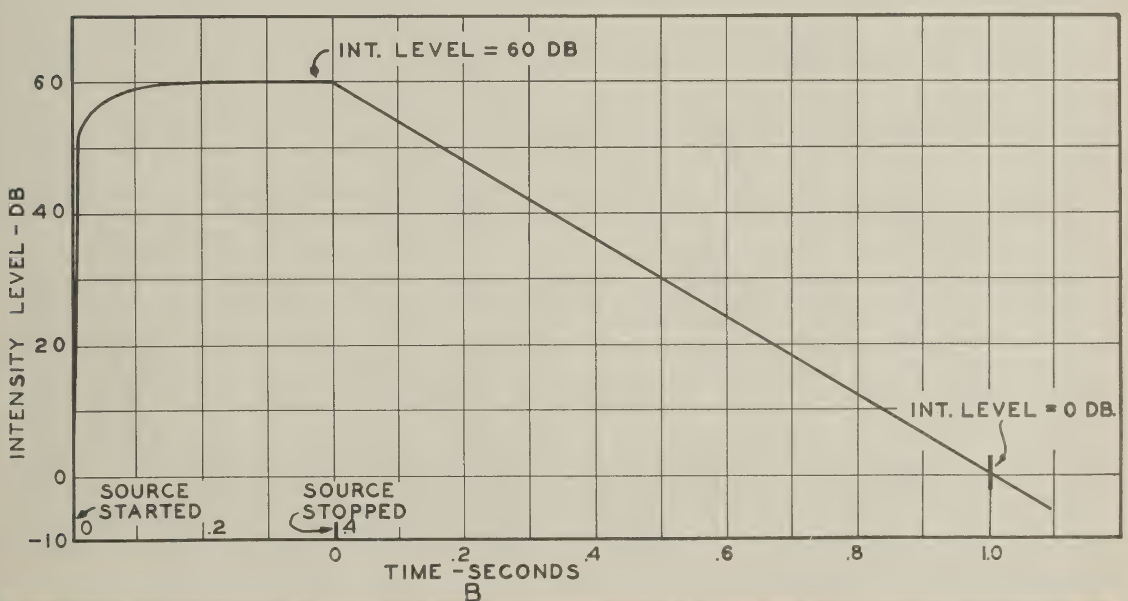


FIG. 4.1—*Curves showing sound decay in a room having a reverberation time of 1 second. A—Intensity plotted on arbitrary scale. B—Intensity level plotted on decibel scale.*

locations can be found where the tone will be nearly inaudible. Furthermore, if the frequency of the note is changed, or if any reflective surface or object in the room is moved, the interference pattern will be shifted, and the observer can hear a change in loudness even without moving his position. Interference effects are noticeable to the ear only when the sound source is a pure tone of fixed frequency. Since speech and music contain a large number of frequencies which are constantly changing, interference phenomena are not discernible by the ear and therefore are unimportant in the consideration of hearing conditions.

With a fixed sound source in operation the steady state intensity, although it varies from point to point due to the interference pattern, maintains an *average* value which is uniform throughout the room, except

within a few feet of the sound source where it becomes considerably greater. This average steady state intensity depends only on the acoustic power output of the source and on the total sound absorbing power of the interior surfaces and furnishings.

If the source is suddenly stopped, the intensity immediately starts to decrease or *decay*. The sound decay takes place along an exponential curve; that is, the intensity decreases by equal percentages in equal time intervals. For example, if the sound loses 75 percent of its intensity during the first second, it will likewise lose during the next second or during any second thereafter, 75 percent of the intensity it had at the beginning of that second. It is seen that the intensity drops off rapidly at first, and then more and more slowly, gradually approaching zero. Here again interference effects are observed in that the sound does not actually decay along a smooth curve, but fluctuates within a range the average of which is an exponential curve. These variations can be easily observed by ear in a reverberant room; the sound is heard to die out in "bumps" instead of smoothly.

Reverberation Time

The *reverberation time* of a room is defined as the time required for the average sound intensity to decay to a value one millionth of its initial average steady state value. Reverberation time is given in seconds, and is measured from the instant the sound source is stopped. The reverberation time of any room depends only on its size and sound absorbing properties, and not on the power of the source nor on the steady state intensity.

Figure 4.1 illustrates graphically the building up and decay of sound intensity in a room having a reverberation time of 1 second, a value which is favorable for the understanding of speech. In Figure 4.1-A, the intensity is plotted on an arbitrary scale chosen so that the steady state intensity is equal to 1,000,000 units. When the sound source is started, the intensity rises quickly and reaches its steady state in less than half a second. (In general, this rise is too sudden to be easily detected by the ear.) When the source is stopped, the intensity drops off quickly, losing 75 per cent of its initial value during the first 1/10 second. Thereafter it continues to diminish until at the end of 1 second it has dropped to a value of one intensity unit, which is one millionth of the steady state value. After 1 second, of course, the decay continues as before, until the intensity becomes practically indistinguishable from zero.

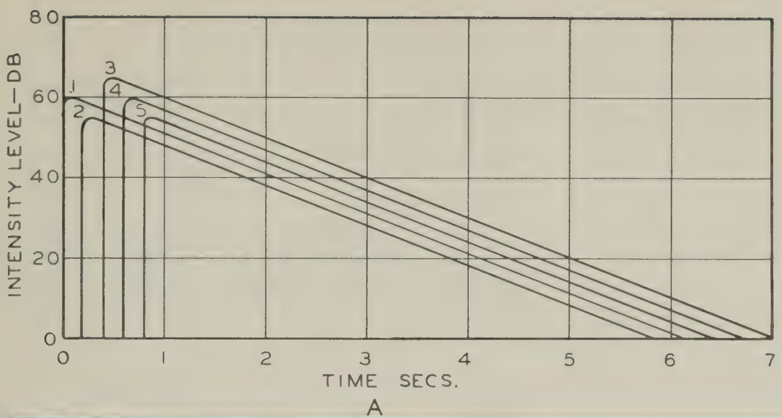
In Figure 4.1-B, the same process is illustrated except that the intensity is shown as *intensity level,* and is plotted on the decibel scale. It is further assumed that the power of the sound source is such that the steady state intensity level is 60 decibels, a level typical of average speech in a small auditorium. It is seen that on the decibel scale the intensity level reaches the steady state value almost instantaneously after the source is started, and that when the source is stopped the decay takes place along a straight line. After 1 second, the intensity level has dropped to 0 decibels, which is 60 decibels below the initial steady state level. Since a difference in intesity level of 60 db. is the same as an intensity ratio of 1,000,000 to 1, the reverberation time may be alternately defined as the time required for the sound intensity level to decay to a value 60 decibels below its initial steady state value.

Rate of Decay

The steepness of the decay curve when plotted on the decibel scale, as in Figure 4.1-B, is called the *rate of decay* of the reverberant sound. It is measured in decibels per second and is obtained by dividing 60 by the reverberation time. The rate of decay and the reverberation time of a room are thus directly interrelated, and either figure can be used equally well for studying the effect of reverberation on hearing conditions. The reverberation time is most commonly used for this purpose, although the rate of decay gives the desired information a little more directly, as shown in Figure 4.2.[1]

Figure 4.2-A represents the building up and decay of the sound intensity levels of five successive syllables spoken at average speed and with normal inflection in an auditorium having a reverberation time of 6 seconds. This is an excessively reverberant condition, and would cause extreme difficulty in understanding speech. The various syllables, which are numbered in order of utterance, are normally spoken with varying voice power, and therefore reach different steady state intensity levels. However, the rate of decay for all syllables is the same, namely 60/6, or 10 db. per second, which is slow enough to cause excessive blurring and overlapping of the sounds of the different syllables. The figure shows that

[1]F. R. Watson, J. Acous, Soc. Am., Vol. 1, p. 47, 1929



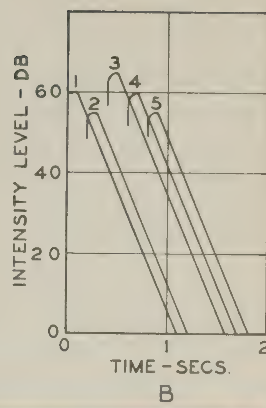


FIG. 4.2—*Decay of successive speech sounds for reverberation times of* (A) *6 seconds and* (B) *1 second.*

three of the syllables, Nos. 2, 4, and 5, are completely drowned out by the reverberant sound of the other two. If the speaker were to talk much more slowly, the sound of each syllable would have more time to die out before the next one was spoken, and the resulting decrease of overlapping would improve intelligibility somewhat. This is the reason that a well trained public speaker talks slowly in a reverberant auditorium.

Figure 4.2-B shows the same five syllables being spoken, but the reverberation time has been reduced from 6 seconds to 1 second, and the rate of decay correspondingly increased from 10 to 60 db. per second. Here the sound of each syllable has died out to a much lower level by the time the next syllable is spoken, and each syllable is free from interference or blurring by any other syllable. As mentioned above, a reverberation time of 1 second has been found to insure practically perfect intelligibility of connected speech.

Audible Duration of Reverberant Sound

Reverberation time is sometimes defined loosely as the length of time a sound can be heard after its source is stopped. This audible duration would depend not only on the acoustical characteristics of the room itself, but also on the power of the sound source, the hearing acuity of the particular observer, and on the deafening effect of whatever extraneous noise happened to be present. With the standard definition given above, the reverberation time is a fundamental acoustical property of the room, and does not depend on any human element.

Factors Determining Reverberation Time—Sabine Formula

Bearing in mind that reverberant sound waves travel in a room at a fixed speed, and that they lose energy only by absorption at the room surfaces, it will be apparent that the longer the average length of path between reflections the more slowly will the sound energy die out, and also that the higher the average absorption coefficient and the larger the area of the room surfaces, the more rapidly will the sound die out. These two opposing factors can be reduced, respectively, to the volume of the room, V, and the total absorption in the room, a, which are related to the reverberation time, T, by the simple formula

$$T = \frac{.05\,V}{a}$$

This is known as the Sabine Formula. The reverberation time T is measured in seconds, and the volume V in cubic feet. The total absorption a involves both the areas and the absorption coefficients of all the room surfaces and furnishings, and is measured in *sound absorbing units* (frequently termed *sabins*).

Sound Absorbing Units

One sound absorbing unit is defined as one square foot of a surface having an absorption coefficient of 100 percent. An open window of one square foot area is equivalent to one sound absorbing unit, because all of the sound that strikes it passes on to the outdoors, and as far as the room is concerned the open window has an

absorption coefficient of 100 percent. Two square feet of open window would furnish two absorption units, and 100 square feet would furnish 100 units. If a surface having a 50 percent absorption coefficient were substituted for the open window, each square foot would furnish only half a unit, and it would require two square feet to furnish one unit. Thus, the number of sound absorbing units furnished by any surface is equal to its area in square feet multiplied by its absorption coefficient.

The total absorption *a* in a room is equal to the sum of the number of units furnished by each of the interior surfaces, plus the number of units furnished by objects such as chairs or the members of an audience. Details of the method of calculating absorption will be given in a later chapter.

Application of Sabine Formula

The Sabine formula was derived by Prof. Wallace C. Sabine of Harvard University from the results of a carefully controlled experimental investigation which he carried out at the beginning of the century.[2] The same formula has subsequently been derived by others from a purely theoretical approach. The formula states, or implies, that (1) the reverberation time is a basic acoustical characteristic of a room and depends only on the volume and on the total absorption of that room, and not on the room shape nor on the position of either the source or the observer; and that (2) if the reverberation time is lowered by introducing additional sound absorbing material into the room, the amount of the reduction will be determined only by the number of additional sound absorbing units introduced, and not by the area, coefficient, location, or method of distribution of the absorbing material. The accuracy with which these predictions are realized in actual cases depends on how closely the conditions in an individual room approach the theoretical assumptions and the experimental conditions on which the formula is based. Fortunately this agreement is sufficiently close in the majority of cases that the Sabine formula may be used to calculate the reverberation time of rooms with satisfactory accuracy.

There are of course certain cases in which actual conditions in a room are such that the formula would lead to quite erroneous results. These cases will be discussed in the next chapter.

[2]*Collected Papers on Acoustics*, Wallace Clement Sabine, Harvard University Press.

Reverberation and Speech Intelligibility— Percentage Articulation

We have seen in a general way from Figure 4.2 how excessive reverberation causes difficulty in understanding speech. A more precise relation between reverberation and speech intelligibility has been determined experimentally by V. O. Knudsen.[3] This was done by measuring the *percentage articulation* (P.A.) in rooms having different reverberation times. In testing a room by this method, a caller reads off a list of unrelated words selected so as to include all of the vowel and consonant sounds of speech in their normal distribution. Each of a group of observers stationed around the room writes down each word as he hears it. The average percentage of the speech sounds heard correctly by the observers is called the percentage articulation for that room. Knudsen's tests showed that an articulation of approximately 96 percent is the highest that can be obtained under the best possible hearing conditions. This record was obtained outdoors, with no reverberation or interfering noise, and with the observers stationed within a few feet of the caller, thus insuring adequate loudness. Further tests indicated that if the articulation in an auditorium is 85% or more, connected speech can be understood with no effort, and hearing conditions for speech may be considered practically perfect. If the articulation is 75% speech can still be understood satisfactorily, but some effort is required. With 65% articulation, speech can be understood only by the closest concentration, and listening is quite fatiguing. When the articulation drops below 65%, hearing conditions for speech are definitely unsatisfactory.

Knudsen's data on the effect of reverberation time on the percentage articulation is shown by the curve in Figure 4.3.[3] These values indicate the articulation percentages that can be obtained in any room when the reverberation time is the only factor influencing hearing conditions, other factors such as loudness and freedom from interfering noise being ideal. The curve shows that the P. A. increases continuously as the reverberation time is lowered.

[3]V. O. Knudsen, J. Acous. Soc. Am., Vol. I, p. 56, 1929
V. O. Knudsen, *Architectural Acoustics*, John Wiley & Sons, Inc., New York.

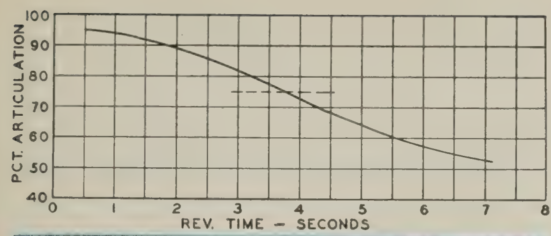


FIG. 4.3—*Curve showing relation of percentage articulation to reverberation time.*

LOUDNESS

Loudness and Speech Intelligibility

It is of course obvious that speech cannot be understood if it is not loud enough. The effect of loudness on intelligibility has been determined by engineers of the Bell Telephone Laboratories.[4] The intensity level in decibels of speech transmitted through a high quality telephone system was set at various known values, and measurements of percentage articulation were taken for each setting. The results are shown in the curve of Figure 4.4, [3,4] which indicates that intelligibility is en-

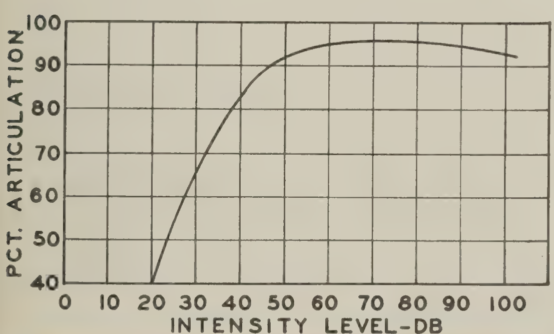


FIG. 4.4—*Relation of percentage articulation to intensity level.*

tirely satisfactory for any intensity level between 40 and 90 db. As the level is reduced below 40 db., however, the articulation drops off very rapidly and speech becomes extremely difficult or impossible to understand for any level below about 30 db. This shows very clearly why the loudness of speech must be maintained at an adequate level in every part of an auditorium in order to insure good hearing conditions for speech. Here again, the articulation percentages shown in Figure 4.4 for a given intensity level can be actually obtained only if all other hearing conditions are perfect. If the reverberation time is too great, or if there is interfering noise present, the P.A. will not be as high as the curve shows, even though the loudness is at the most favorable level.

[4]Harvey Fletcher, *Speech & Hearing,* D. Van Nostrand Co. Inc., New York.

Factors Governing Loudness

The reverberation theory tells us that the steady state intensity created by a sound source is directly proportional to the acoustic power output of the source, and inversely proportional to the number of sound absorbing units in the room, and depends on no other factors. Applying this to a speaker in an auditorium, the stronger the speaker's voice, the greater will be the average loudness of the speech as heard by the audience, which is of course quite obvious. At the same time, the greater the amount of absorption in the room, the less will be the average loudness throughout the room. In other words, if the absorption in an auditorium is doubled, a speaker would have to double the power of his voice in order to maintain the same average loudness over the seating area.

A large auditorium will in general contain more absorption than a small one, so that a speaker must exert greater voice power to maintain adequate speech loudness throughout a large auditorium than is necessary in a small one. The average speaker will instinctively adjust his voice power to the size of the auditorium, but usually this compensation is not enough to maintain sufficient loudness. Some speakers have naturally weak voices, and can therefore raise their voice power to only a limited degree. Very frequently speakers are inexperienced, and do not properly estimate the amount of voice power required. Finally, an auditorium may be so large and contain so much absorption that the maximum voice power of which a speaker is capable is insufficient to maintain the required loudness throughout the entire room.

Knudsen[3] has given an interesting comparison of the loudness of speech as measured in two rooms, one a small lecture hall of 27,200 cu. ft. volume, and the other an auditorium of 240,000 cu. ft., a size typical of many high school auditoriums. The average intensity level in decibels of the speech of a number of persons was measured at a point near the center of each room, dur-

ing regular lectures. The average intensity level in the small room varied from 44.7 to 56.2 db. between six different speakers, with an average for the six of 50.7 db. The intensity level of individual speakers varied by as much as 30 db. from moment to moment. In the large room the average intensity level for eight speakers was only 45.7 db., with individual variations similar to those observed in the small room. The speakers in the large room expended on the average nearly twice as much voice power as those in the small room, but, as evidenced by the lower average intensity level in the large room, this increase in voice power was not enough to overcome the effect of the greater absorption in the large room. To summarize: the larger the room, the greater are the chances that the average speaker's voice will not be loud enough to be understood easily in every part of the room.

Combined Effects of Loudness and Reverberation Time on Speech Intelligibility

We have seen how either inadequate loudness or excessive reverberation can reduce the percentage articulation in a room and detract from speech intelligibility. The combined effects of these two factors are shown in

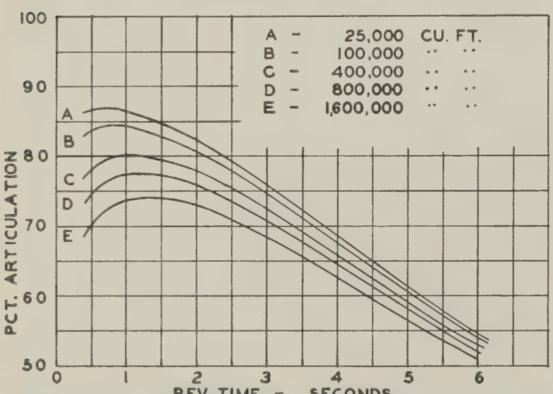


FIG. 4.5—***Curves showing relation of percentage articulation to reverberation time in auditoriums of different volumes, assuming direct speech of average power.***

Figure 4.5,[3] which has been prepared by Knudsen from the data in Figures 4.3 and 4.4 and from his measurements of the average voice power of speakers. These curves show the relation of the P.A. to the reverberation time in rooms of various sizes ranging from 25,000 to 1,600,000 cu. ft. The curves are all based on the assumption of an average speaker who possesses normal voice capacity and adjusts his voice power to the size of the room in the average manner.

A number of useful facts may be gathered from these curves:

1. For any given reverberation time, the P.A. decreases continuously as the size of the room increases. This is caused directly by the decrease in speech loudness with increasing room size, which in turn is due to the fact that for a given reverberation time a large room must contain more absorption than a small room. As described above, the average speaker does not or can not fully compensate for this higher absorption by raising his voice power.

2. For any given room size, as the reverberation time is decreased the P.A. increases up to a peak value, after which it begins to fall off. In the portion of the curve to the right of the peak, the reverberation time is the controlling factor. However, as the reverberation time is further lowered by introducing more absorption into the room, the absorption becomes so great that it reduces the loudness to a harmful extent. The portion of the curve to the left of the peak indicates this condition, where the gain in articulation caused by lowering the reverberation is more than offset by the loss in articulation caused by diminishing the loudness. The peak lies at the best possible reverberation time and loudness. It is therefore quite possible to bring the reverberation time too low in a room intended for unamplified speech, particularly in large rooms. The value of reverberation time which gives the highest possible P.A. varies from about .8 seconds for a volume of 25,000 cu. ft. to 1.3 seconds for a volume of 1,600,000 cu. ft.

3. A greater range of reverberation time is allowable in small rooms than in large rooms. In the room of 25,000 cu. ft. volume, the P.A. is above 75% for any reverberation time up to 3 seconds and is better than 85%, which means practically perfect hearing conditions, for any reverberation time less than about 1.5 seconds. For the 800,000 cu. ft. room, however, the P.A. lies above 75% only within a much narrower range of reverberation times, namely .5 to 1.9 seconds, and the best possible reverberation time of 1.2 seconds brings the P.A. only up to 77%, which is satisfactory, but considerably short of perfect. The curve for the room of 1,600,000 cu. ft. shows that satisfactory hearing condi-

tions cannot be obtained, with the average speaker, no matter at what value the reverberation time is placed.

The curves in Figure 4.5 apply only to the "average" speaker. As we have seen above, the voice power of

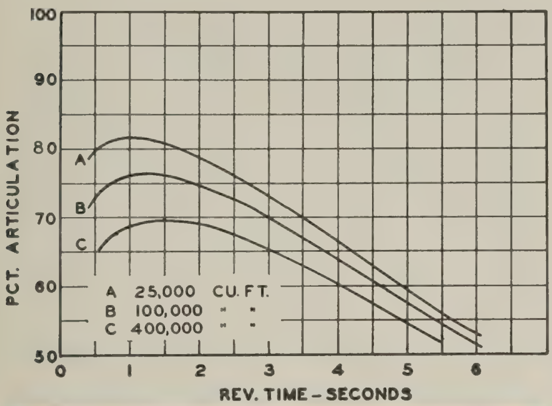


FIG. 4.6—*Relation of percentage articulation to reverberation time and room volume for weak speaker.*

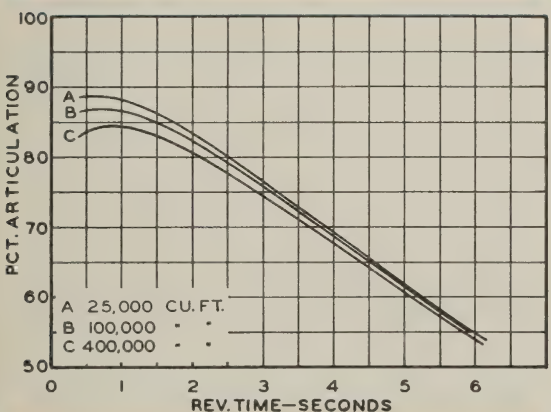


FIG. 4.7—*Relation of percentage articulation to reverberation time and room volume for strong speaker.*

different speakers varies considerably, depending on their voice capacity and on their experience and training. Figures 4.6 and 4.7 give the same type of information as Figure 4.5, except that they apply to the case of a very weak speaker and a very strong speaker, respectively. These curves have been prepared by the author from Knudsen's data, and are based on the weakest and strongest measured voice powers of a group of 14 university instructors observed in his experiments. These two cases probably represent about the average range of variation between individual speakers in the majority of auditoriums, although occasionally even weaker voices might be encountered, as in court rooms or in children's performances.

By comparing Figures 4.5, 4.6 and 4.7, it is seen at once that, as would naturally be expected, a strong speaker can be understood satisfactorily in a larger room than can a weak speaker, and that in a room of a given size the stronger the speaker's voice the better will be the intelligibility. Also, in a room of a given size, satisfactory hearing conditions can be obtained for a wider range of reverberation times with a strong speaker than can be obtained with a weak speaker.

Public Address Systems

If a speaker's voice is amplified and projected into an auditorium by loud speakers, the limitation imposed on speech intelligibility by the loudness is entirely removed, since the loudness can be maintained at the best possible level under all conditions simply by adjusting the volume control of the amplifier. The reverberation time then remains the only factor influencing intelligibility. Figure 4.8 shows the percentage articulation that

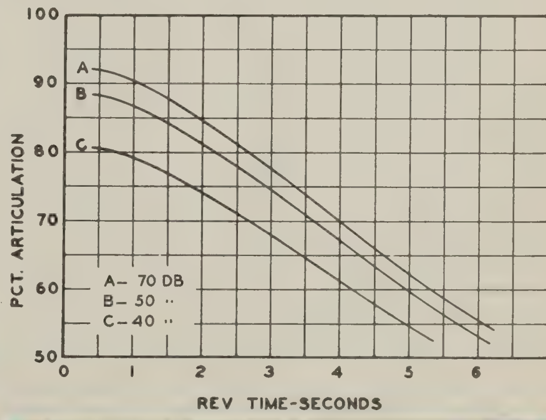


FIG. 4.8—*Relation of percentage articulation to reverberation time in a room of any size, with speech amplified to various intensity levels.*

can be expected in any room, regardless of its size or absorption, with a high quality public address system. Each curve gives the relation of the percentage articulation to the reverberation time when the average loudness is held at the indicated fixed level. Figure 4.4 shows

that the highest possible articulation is obtained at an intensity level of 70 db., and that lower levels cause a decrease in articulation, as is also shown by the curves of Figure 4.8. These curves also indicate that: (1) With the loudness maintained constant at the optimum level of 70 db. by a public address system, hearing conditions for speech will be satisfactory (P.A. over 75%) in a room of any size with any reverberation time up to about 3.3 seconds, and practically perfect (P.A. over 85%) with any reverberation time up to about 2 seconds. (2) There is a negligible difference in hearing conditions caused by a change in average loudness from 70 to 60 db., but with a level of 50 db., the intelligibility starts to fall off rapidly, and the reverberation time must be held within a considerably narrower range to insure satisfactory hearing conditions.

Questions often arise as to the relative merits of a public address system as against acoustical treatment in planning auditoriums, or in cases of poor hearing conditions in existing auditoriums. These questions can be answered from the information given in Figures 4.5 to 4.8, from which a few general statements can be made.

(1) A public address system is required in any case where inadequate loudness is a contributing cause of poor speech intelligibility. The larger the auditorium, the less will be the loudness of unamplified speech, and the greater will be the necessity for speech amplification. For auditoriums of less than 50,000 cu.ft. volume, a public address system is of little or no help, since the loudness without amplification will nearly always be sufficient. For volumes of 50,000 to 400,000 cu. ft., speech amplification is advisable, and will be particularly of value for weak speakers and for the larger rooms within this range. For rooms larger than 400,000 cu. ft., a public address system is virtually a necessity. Where intelligibility is further restricted by excessive background noise, such as street traffic, amplification will be found necessary in rooms considerably smaller than the above.

(2) A public address system will not insure entirely satisfactory hearing conditions in any room, regardless of its size, unless the reverberation time is less than about 3 seconds. The lower the reverberation time, the greater is the improvement possible by speech amplification. Conversely, there is no value of reverberation time which will give satisfactory hearing conditions if the average loudness is less than about 35 db. The greater the loudness, the greater is the improvement obtainable by lowering the reverberation, and if the loudness is raised to the optimum level, by speech amplification when necessary, the reverberation time can be adjusted to give practically perfect hearing conditions in a room of any size.

By carefully engineered installations of public address systems it has been possible to obtain fairly acceptable hearing conditions in very large rooms such as cathedrals, where architectural features do not permit the installation of adequate absorption. The adverse effects of excessive reverberation may be partially overcome by the use of multiple loud speaker units distributed around the room so as to blanket the seating area in as close proximity as possible.

Requirements for Public Address Systems

It is obvious, of course, that a public address system must be capable of sufficient amplification and acoustic power output to raise the average loudness to the required level in the room in which it is installed. As pointed out above, the average intensity level must be maintained between 60 and 70 db. in order to insure maximum intelligibility. It has been found that a level of about 65 db. gives the most comfortable loudness. At the same time, the system should have enough reserve power capacity to produce levels as high as 75 or 80 db. without overloading or distortion, in order to handle possible momentary peaks in the loudness of the speaker's voice.[5]

The system must also be able to transmit uniformly and without distortion a wide range of frequencies. Articulation tests have shown that it is necessary to reproduce all frequencies between 200 and 8,000 cycles in order to provide the highest possible speech intelligibility. However, a system which transmits frequencies only up to 4,000 or 5,000 cycles will insure very nearly the same intelligibility, although the naturalness of the speech is decreased. As the frequency range is reduced below 4,000 cycles, the intelligibility drops off rapidly. Frequencies below 200 cycles are not required for intelligibility, but are necessary, down to about 75 cycles, to preserve naturalness.

The loud speakers should in general be installed as close as possible to the position of the actual speaker,

[5]S. K. Wolf and W. J. Sette, J. Acous. Soc. Am., Vol. II, p. 384, 1931.

both in order to preserve the audience's impression that the sound is coming from the actual speaker's mouth, and in order to prevent any noticeable time difference between the arrival of the sound from the actual speaker and that of the sound from the loudspeakers. If this time difference is too great, and if the direct sound is loud enough in relation to the amplified sound, it is possible for the audience to hear a distinct doubling or repetition of the sound, which is distracting and which may interfere with intelligibility. However, in installations where the actual speaker is concealed from the audience and where the loudness of his direct speech is much less than that of the loudspeakers, the latter may be placed in any suitable location.

Most loudspeakers are directional; that is, they project sound more efficiently directly in front of them than in any other direction. This directional effect is most pronounced at the high frequencies, on which speech intelligibility depends. Therefore, a large enough number of loudspeaker units should be installed, and they should be so located and directed, that every part of the seating area is included within the "beam" from one or another of the units. This means that in auditoriums having under balcony spaces, the loudspeakers should be placed low enough to be within sight of every seat under the balcony.

Effects of Room Shape on Loudness

The data given in Figures 4.5 to 4.7 showing the intelligibility of unamplified speech as related to the size and reverberation time of an auditorium are all based on the assumption that the loudness is essentially uniform over the entire seating area. Actually, the distribution of loudness is not uniform, but instead is somewhat greater at the front of the room than at more distant points. This explains why one chooses a front seat for the best hearing of speech, and why articulation tests in auditoriums show higher intelligibility in the front of the room than in the rear. This variation in loudness is not detrimental to hearing conditions provided the loudness is at least adequate at every seat in the room, as is the case in small rooms or with properly amplified speech. However, in large rooms, with unamplified speech, it often happens that hearing conditions are satisfactory only in some parts of the seating area.

There are a number of features of room shape which tend to emphasize this non-uniform loudness distribution and which should be avoided in good acoustical design. In the first place, if the front of the seating area is too wide, intelligibility will be poor in the front corners. The reason for this is that the human voice has directional characteristics much the same as a loud speaker. This is easily observed by noting how much more distinct is a person's speech when he is facing the listener directly than when his head is turned to one side. If there is too wide an angle between the speaker and the front corner seats of an auditorium, the high frequency components of the speech will not be transmitted as efficiently to these corner seats as to the center seats, and a consequent loss of intelligibility will result. Excessively wide seating areas are sometimes found in school gymnasium-auditorium designs in which the stage is placed along one side of the room instead of at one end.

Low, deep under balcony spaces are particularly conducive to non-uniform loudness distribution. The total amount of sound energy that can enter the space is restricted by the under balcony opening, and its intensity is further reduced in travelling to the rear of the space by the absorbing action of the audience. In order to avoid excessive diminution of loudness at the rear seats, the height of an under balcony space at the front should be as great as possible, and the depth should be not more than three times, and preferably not more than twice the height at the front.

Reinforcement of Loudness by Reflecting Surfaces

It is possible to obtain more uniform distribution of loudness throughout an auditorium by utilizing the first reflections of sound from wall and ceiling surfaces. The total sound received at any seat in an auditorium may be roughly divided into three components, (1) the direct sound, (2) the sound which has been reflected once or twice, and (3) the generally reflected sound, as shown in Figure 4.9.

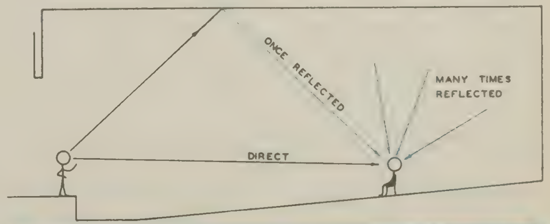


FIG. 4.9—*Components of sound received by a listener in an auditorium.*

The loudness of the direct sound is not affected in any way by the room surfaces, but depends only on the

strength of the speaker's voice and on the distance of the listener from the speaker, in accordance with the inverse square law. Since the direct sound travels in a straight line, it is always the first component to arrive at the listener's ear. The direct sound is followed immediately by the second component of the total sound, namely those waves which have been reflected once or twice before reaching the listener's ear. The loudness of each of these waves is less than that of the direct sound (if they are reflected from plane surfaces) because they have travelled over a longer path and have also lost some energy by absorption at the reflecting surface. The generally reflected sound, comprising the third component, includes all the rest of the sound waves which reach the ear after a large number of reflections.

Each of these three groups contributes to the total loudness, but it is the loudness of the first two groups, namely the direct and the once or twice reflected waves, which largely determines the intelligibility of speech. The reason for this is that the first reflections arrive at the ear so soon after the direct sound that they practically coincide with it and tend to amplify its loudness. The louder the reflected sound in relation to the direct sound, and the sooner it arrives at the ear after the direct sound, the greater will be this reinforcing effect. The generally reflected sound adds considerably to the total loudness, but these waves for the most part arrive after a long enough delay that they tend to cause a blurring effect which is not favorable to speech intelligibility.

It has been found that all reflected waves which arrive at the ear within about 1/17 second after the direct wave bring about useful reinforcement of the direct sound. This time difference corresponds to a difference in the length of path traversed by the direct and reflected waves of about 65 feet. In order to utilize this reinforcement in auditorium design, therefore, it is necessary to shape the walls and ceiling in such a way that as many of the reflected waves as possible will traverse paths from the source to each listener which are less than 65 feet longer than the path of the direct sound.

Design of Stage

One of the simplest and most effective means of securing reinforcement of the direct sound is to provide a hard, reflecting wall surface immediately behind the speaker's position. This possible reinforcement is all too frequently lost in the average auditorium, where the speaker stands either in front of a highly sound absorbent velour stage curtain which provides negligible reflection, or on an open stage completely lined with absorbent hangings. Knudsen tested the effect of placing a large portable reflector directly behind a speaker on

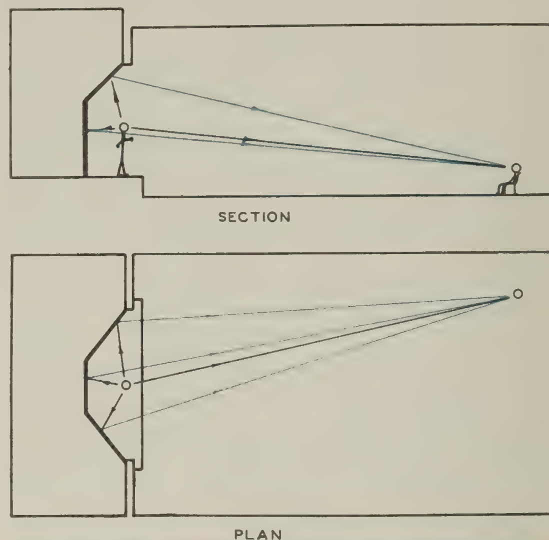


FIG. 4.10—*Reinforcement of direct sound by reflection surfaces on stage.*

such a stage and found an increase in articulation of 3 percent. This improvement is not large, but is certainly worth while. Considerable further improvement can be obtained by arranging other reflecting surfaces above and at the sides of the speaker's position. This is illustrated in Figure 4.10, which shows how the direct sound is amplified by four reflected waves, one each from the three wall segments and the sloping ceiling surface. Reflectors such as these may be installed either permanently or in the form of moveable sets of hardboard or plywood.

Design of Auditorium

The reinforcing effect of reflected sound may be further utilized in the design of the auditorium proper, to produce more uniform loudness distribution. This is essentially a matter of flaring the wall and ceiling surfaces near the stage outward and upward so that the sound is reflected toward the rear of the room, where reinforcement of the direct sound is most needed, and so that the arrival of the reflected sound at the rear seats follows that of the direct sound after as short a time delay as possible. It is also advantageous to keep the ceiling only as high at every point as is necessary

to allow clear sight lines and proper architectural proportions. Excessively high ceilings tend to produce long-

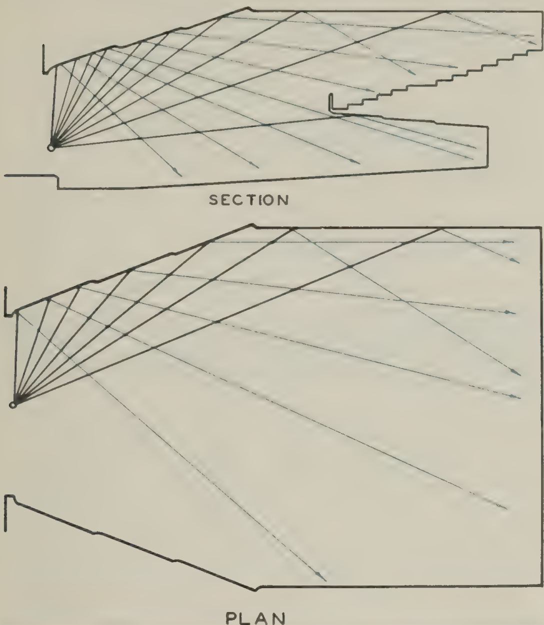


FIG. 4.11—***Auditorium designed to provide maximum reinforcement of direct sound.***

delayed reflections which provide little or no reinforcement of the direct sound.

A typical design illustrating the principles outlined above is shown in Figure 4.11. It will be noted that the front portions of the side walls and ceiling are sloped so that every part of the seating area receives reflected sound which follows the direct sound closely enough to provide effective reinforcement. The rear seats above the balcony are further benefited by reflections from the straight portions of the side walls and ceiling, and the under balcony seats similarly receive additional reinforcement from the straight parts of the side walls and from the sloped under balcony ceiling.

By way of comparison, Figure 4.12 illustrates poor acoustical design. The excessively high ceiling produces reflections which are so long delayed that they afford little or no reinforcement to any part of the seating area; the rear seats both above and below the balcony receive only the reflections from the side walls, and no reflected sound whatever from any of the ceiling surfaces; and the front portions of the side walls direct the sound back across the room instead of toward the rear

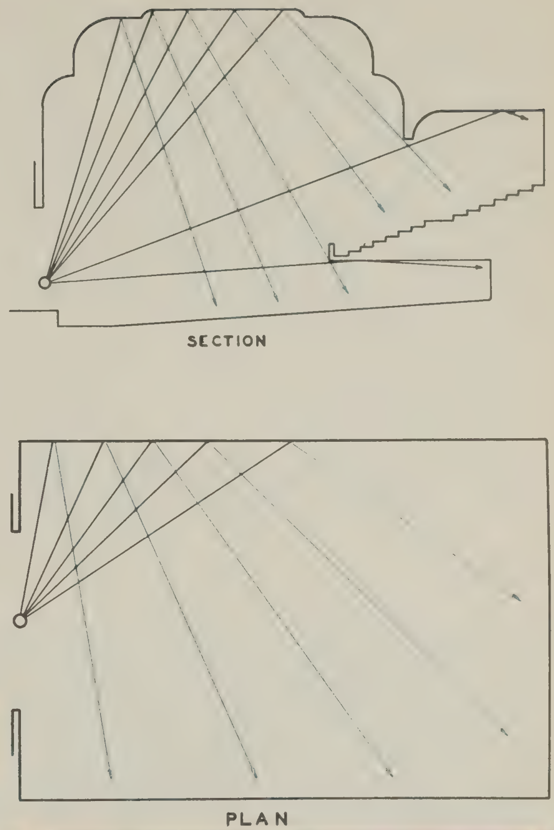


FIG. 4.12—***An auditorium design which produces interference due to long-delayed reflections.***

where it would do more good.

It should be pointed out that a design such as illustrated in Figure 4.11 serves only to distribute the sound energy more uniformly throughout an auditorium and to impart greater clarity and "carrying power" to the sounds of speech and music. The design alone, however, should not be depended upon to increase the overall loudness, since, as shown previously, this depends only on the power of the source and on the amount of absorption in the room. The recommendations given in a previous section for the use of public address systems should in general be followed regardless of the design, in order to insure a sufficiently high average level over the seating area.

Placement of Treatment

Detailed recommendations for the location of acoustical material are given in the next chapter. At this point,

however, it should be mentioned that the placement of absorption can be advantageously coordinated with the design principles outlined above. This is done simply by placing the required absorbing material insofar as feasible only on those surfaces which tend to produce interfering delayed reflections. Rear walls and the front portions of excessively high ceilings and widely spaced side walls would be generally suitable for heavy treatment by this criterion. Low ceilings and wall surfaces shaped to provide useful reinforcing reflections are preferably left untreated, treated partially in panels or strips, or treated with low efficiency material.

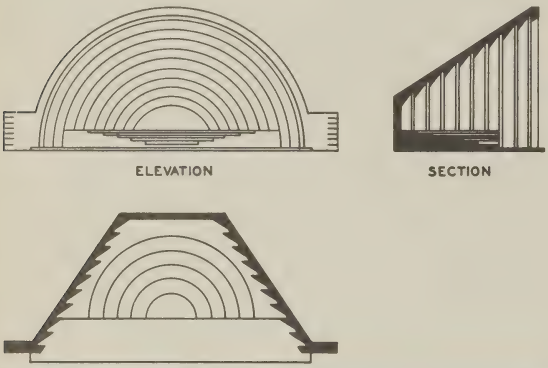


FIG. 4.13—*Band shell designed for efficient projection of sound.*

Outdoor Band Shells

The function of a band shell for outdoor musical performances is to project as much as possible of the total available sound energy toward the audience. It should therefore be designed in accordance with the principles outlined above. It is often erroneously believed that the interior surfaces of a band shell should be lined with a sound absorbing material, which would of course defeat the purpose of the structure. The surfaces should instead be faced with a highly sound reflecting material such as plywood, plaster board or masonry.

The shaping of the walls should be such as to reflect the sound efficiently and uniformly over the audience area. A design which has been frequently used is that of the orchestra shell for the Hollywood Bowl,[6] shown in Fig. 4.13. Knudsen reports that hearing conditions are entirely satisfactory for the musicians themselves, and that the sound is projected with remarkable efficiency

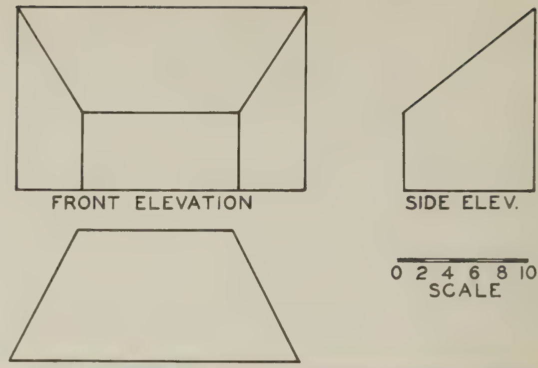


FIG. 4.14—*Band shell of single design providing adequate sound projection.*

over the seating area, but at a certain sacrifice of uniform distribution. The best hearing locations are on the center line of the seating area, and in listening from one side the instruments on the opposite side of the stage are heard more strongly than the others, thus apparently putting the band or orchestra out of balance.

The best compromise between efficient projection and uniform distribution appears to be a design utilizing plane surfaces with side walls and ceiling sloping outward and upward so as to reflect the sound in the proper directions.[7] A typical design is shown in Fig. 4.14. One frequently sees band shells in the form of a perfect quarter sphere. This shape is bad, because it tends to cause focussing of the reflected sound which can be extremely annoying both to musicians and audience. Parabolic shapes are sometimes used, but they also tend to cause spotty distribution over the seating area.

ECHOES AND FOCUSSING

An *echo* is a single reflection of sound which can be heard as a distinct repetition of the original sound. The effect is familiar to anyone who has heard his voice thrown back at him by a cliff or a wall in the open air. Under certain conditions echoes can be heard in an auditorium, where they are at least a source of annoyance to both the speaker and the audience, and sometimes cause difficulty in hearing. An echo in a room differs from reverberation in that it is produced by a single first reflection of sound from some individual surface, and is therefore heard as a distinct doubling or

[6]Reprinted by permission from "Architectural Acoustics" by V. O. Knudsen, published by John Wiley & Son, Inc.

[7]A number of excellent designs are described by Henry L. Kamphoefner, Professor of Architecture, University of Oklahoma, in the September and October, 1945 issues of *Pencil Points* (*Progressive Architecture*).

repetition of a syllable of speech or note of music. Reverberation, as has been described previously, is heard as a continuous prolongation of the sound, due to the rapid succession of reflections from all of the room surfaces.

Conditions Necessary for Echoes

In order for any single reflection of sound to be heard as an echo, rather than as part of the general reverberation, it is necessary first that the reflected sound arrive at the listener's ear at least 1/17th second later than the direct sound, or in other words, that it travel a path from source to listener at least 65 feet longer than the path traversed by the direct sound. If the time lag is shorter than this, the reflection cannot be distinguished by the ear, and will instead act as a reinforcement of the direct sound, as explained in a preceding section.

Secondly, the reflection must be sufficiently loud in relation to other sound in the room in order to be audible as an echo. The longer the total distance that the reflection travels from source to listener, the less will be its loudness at the listener's ear, as stated by the inverse square law (provided the reflection is produced by a plane surface). Also, its loudness will be further reduced by a greater or less amount by the reflecting surface itself, depending on its absorption coefficient. Furthermore, the general reverberation set up by each successive element of speech or music, as well as the direct sound of these elements, tends to mask or drown out the sound of single reflections.

From these considerations we may make several general statements pertaining to rooms with plane surfaces:

1. Echoes are seldom heard in small rooms, because the time lags of first reflections are all too short to produce echoes.

2. Echoes are not generally observable in a room having a long reverberation time, due to the masking effect of the reverberation.

3. Echoes are most likely to occur in rooms seating 500 or more, and having reverberation times short enough to permit satisfactory speech intelligibility, namely, 1 to 2 seconds.

In this latter case, the echoes are almost always produced by reflection from the rear wall, since it is this surface which makes possible the longest path difference between direct and once-reflected sound, when the source is on the stage. The echoes are generally most apparent to the speaker on the stage, and to the auditors who are seated about one-third to one-half of the way back from the stage. This is illustrated in Fig. 4.15, in which the path differences and time lags are shown for various locations on a 50 x 100 foot floor plan. At point *D* the time lag is too short for an echo to be heard. At points *B* and *C* an echo could be heard because the time lag is longer. At point *A* the time lag is still longer, but the echo would probably not be heard because it would be so much weakened by the distance it has travelled.

As a matter of actual fact, echoes in a room with a plane rear wall, such as shown in Fig. 4.15, would in all

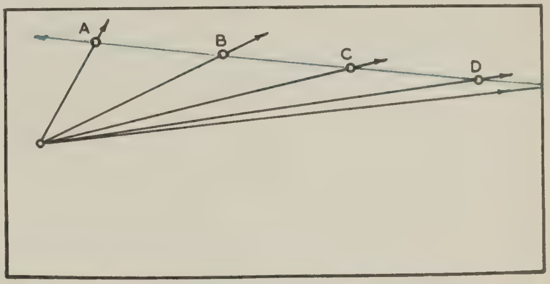


FIG. 4.15—*Plan of room showing difference in time of arrival of direct sound and sound reflected from rear wall to auditors in various positions.*

Position	Path Difference	Time Lag
A	160 ft.	1/7 sec.
B	112 ft.	1/10 sec.
C	70 ft.	1/16 sec.
D	11 ft.	1/100 sec.

probability not be heard at any seat if the auditor were facing the stage and directing normal attention to the stage performance. It is only by carefully listening for echoes, or even by turning one's head toward the rear, that they could be detected. Rear wall echoes are much more apparent to the speaker, however, because he is directly facing the rear wall from which the echoes originate. It is undoubtedly an annoyance to any speaker to have his voice thrown back at him in this way, and it is therefore advisable in any room longer than about 50 feet to reduce rear wall echoes as much as possible. In the case of plane walls, this can be accomplished satisfactorily by treating the wall with an acoustical material having a noise reduction coefficient of at least .60.

Echoes may sometimes be caused by excessively high, horizontal ceilings, such as shown in Fig. 4.12, and are generally most noticeable in the same region in which rear wall echoes are observed. This is another reason for keeping the ceiling at a moderate height. When a

high ceiling is necessary for architectural reasons, however, acoustical treatment of the ceiling can be used to control echoes successfully.

Focussing of Sound

The discussion of echoes has pertained thus far to reflection from a plane surface, in which case the sound rays continue in divergent paths after reflection in the same manner as before reflection, and diminish in intensity as they progress. Difficulties due to echoes may become much more serious when reflections take place from concave room surfaces. A comparison of sound reflection from a plane surface and a concave surface is shown in Fig. 4.16. It is seen that the concave surface

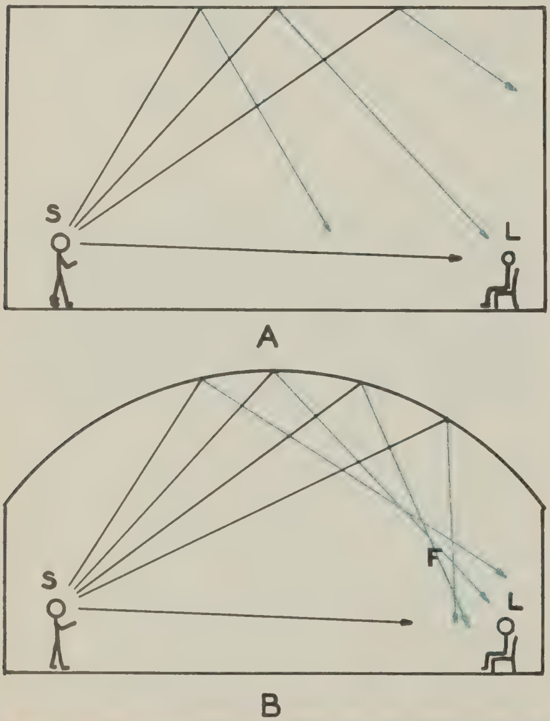


FIG. 4.16—*Diagrams showing* (A) *divergent reflection from a flat ceiling, and* (B) *focussed reflection from a curved ceiling.*

converges and *focusses* the reflected rays in the same manner that a concave mirror focusses light rays. As the waves converge, the sound increases in intensity, since the same amount of sound energy becomes concentrated into a smaller space. At the focal point, *F*, the intensity becomes almost as great as at the actual source, *S*, after which the rays diverge once more and the intensity again diminishes.

If a listener is stationed at a point *L*, near the focal point, the focussed sound from *F* will be much louder than the direct sound from *S*, and he will experience the illusion of seeing a speaker on the stage but hearing his voice apparently coming from a point in mid-air a few feet overhead. If the path difference is long enough, he will hear a focussed echo which is much louder than the direct sound, and which may cause speech to be unintelligible. If the listener's ear happens to coincide with the focal point, *F*, the sound will appear to come from "everywhere and nowhere" but not from its actual source, *S*. Such effects are indeed interesting, but are certainly not conducive to pleasant or satisfactory hearing conditions.

Curved Rear Walls

The most common occurrence of a concave room surface is the curved rear wall of the average theatre or auditorium, as shown in Fig. 4.17. The center of curva-

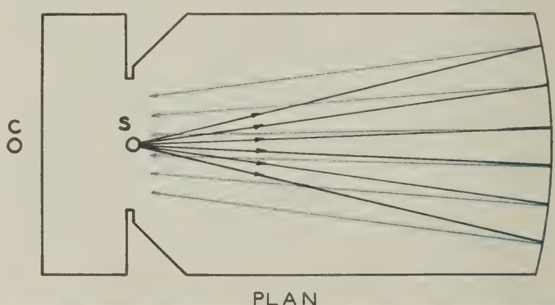


FIG. 4.17—*Reflection from a curved rear wall having the center of curvature at point* **C.**

ture, *C*, usually lies near the outer stage wall, as shown, so that a focal point is not formed inside the auditorium. However, the reflected sound converges enough to form a rear wall echo which is considerably louder than would be produced by a plane wall, and which is very liable to cause trouble. A curved rear wall should be avoided in auditorium design, being replaced with either a straight wall or a stepped or splayed contour as suggested in Fig. 4.18. The splayed wall serves to scatter the sound instead of reflecting it regularly back toward the front of the room. Another measure which is very effective is to slope the rear wall inward a few degrees so as to reflect the sound immediately down into the rear seats, where it is scattered and absorbed. The entire rear wall surface should be acoustically treated in any case.

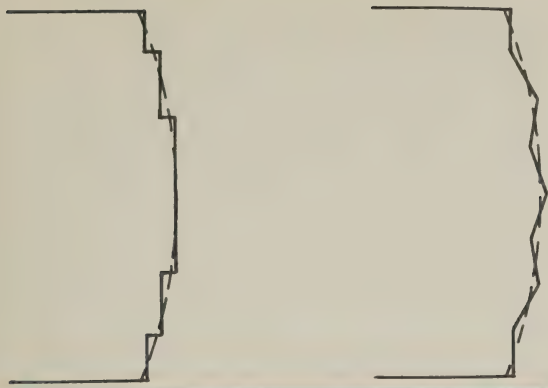


FIG. 4.18—*Methods of breaking up a curved rear wall to avoid focussed reflection.*

In existing buildings where structural changes cannot be made, the only means at hand is to cover the entire rear wall surface with as highly efficient an acoustical material as possible. In the majority of cases this will reduce echoes to the point where they are normally unnoticeable to the audience, but it cannot be considered as a 100 percent cure.

which three ceiling curvatures are shown in cross section. The arcs shown can be considered to represent either cylindrical or spherical surfaces. In case A, where the center of curvature lies just above the floor line, sharp focussing occurs very close to the audience, with the consequent freak effects and poor hearing conditions described above. In case *B* the radius of the ceiling is more than twice the ceiling height, causing the sound to be reflected in nearly parallel rays. This will produce no harmful effects for ceilings of moderate height, and if the ceiling is low enough to produce a short time lag and a consequent reinforcing effect of the reflected sound, the reinforcement will be slightly enhanced and the sound distribution correspondingly improved. In case *C*, typical of a barrel vaulted church, focussing takes place inside the room, but the focal point is far enough above the audience that its effects are not ordinarily noticeable. It is always wise, however, to minimize the possibility of trouble either by breaking up the ceiling with large, deep coffers, or by the use of efficient acoustical treatment. Smaller curved surfaces, such as coves, will generally cause no difficulty and require no special treatment.

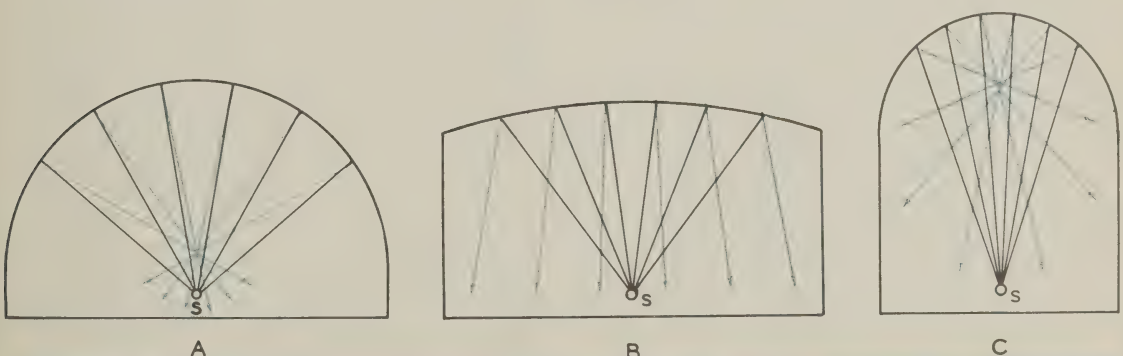


FIG. 4.19—*Reflection from curved ceilings having various radii. A— Center of curvature near floor line. B—Radius of curvature more than twice the ceiling height. C—Radius of curvature less than half the ceiling height. Condition A produces the most severe focussed echoes.*

Curved Ceiling Designs

Severe focussed echoes from single or double curved ceilings occur when the center of curvature lies near the floor line. To avoid this condition, *the radius of curvature of the ceiling should be less than half or well over twice the peak ceiling height.* This is a simple but extremely important rule. Violations of it have more than once made rooms almost totally unusable as auditoriums.

An explanation of the rule is shown in Fig. 4.19, in which three ceiling curvatures are shown in cross section.

It should be pointed out that in applying this rule to auditoriums with balconies, the ceiling height measured from the balcony should be considered as well as the height above the main floor, for the reason that a curved ceiling surface might produce focussed echoes in the balcony, while causing no trouble for the main floor seats. This is illustrated in Fig. 4.20, which is representative of certain older types of auditorium designs.

It should also be remembered that focussing action is

much more pronounced, and its effects more serious, when it is produced by a double curved surface such as a dome, than when caused by a single curved surface.

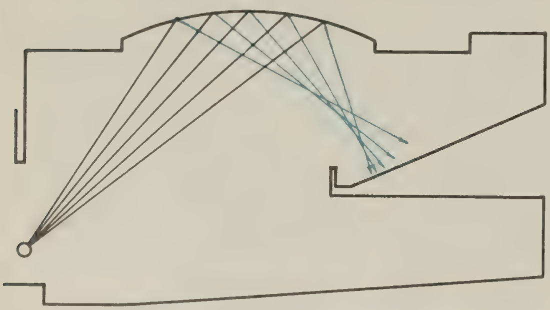


FIG. 4.20—Diagram showing how a curved ceiling can produce focussed echoes in the balcony but not on the main floor.

Curved Shapes in General

The auditorium designer should bear in mind that while curved shapes may be more pleasing architecturally than rectangular designs, they are potentially dangerous from the acoustical standpoint, and should be carefully analyzed for focussing effects, and corrected if necessary while in the sketch stage. Disregard of this precaution may lead to acoustical defects so severe that nothing less than complete remodelling of the room will bring about a satisfactory correction.

A good example of this was the construction of a large municipal auditorium which was designed as a perfect hemisphere with the center of curvature only a few feet above the floor line. Although the entire wall and ceiling surface of the room was acoustically treated, focussed echoes were so bad that the auditorium could not be used. By practically reconstructing the building it was possible to flatten out partially the curvature of the walls and ceiling. With this accomplished, and a more efficient type of acoustical treatment substituted, the auditorium is now usable for the purpose intended, but is still far from perfect. It may be remarked in passing that if more efficient acoustical treatment had been applied without changing the shape of the room, the intensity of the echoes would have been slightly reduced, but the reverberation and its masking effect would have been so much decreased that the echoes would probably have been more noticeable than before. Certainly an attempt to remedy the trouble by acoustical treatment alone would not have been successful.

If designs involving extended curves must be used, it is essential that the surfaces have long radii of curvature, with their centers lying well outside the room. If a circular or semi-circular floor plan is desired, it should be followed only in general contour. The actual wall surfaces should consist of segmented or splayed plane surfaces, or convex curved segments, or should be broken up in some other manner in order to prevent regular reflection and consequent focussing. The same measure should be applied to ceiling surfaces whose centers of curvature lie near any part of the seating area.

Multiple Echoes

A multiple echo, or "flutter," is one in which several repetitions of the original sound can be heard in regular and more or less rapid succession. It can occur only when both the sound source and the listener's ear are on the same perpendicular line joining two parallel reflecting surfaces, and is due to the reflection of the sound back and forth between the surfaces and through the listener's ear position. A multiple echo is most easily observed between a pair of smooth, unbroken, highly reflective walls in a fairly small room with a low reverberation time, as in a private office with an acoustically treated ceiling, or in a bedroom with a carpeted floor.

Multiple echo seldom occurs in auditoriums to any harmful extent, but may create a serious disturbance in radio and recording studios. This will be covered more fully in a later chapter.

Proper Methods of Testing for Echoes

It frequently happens that an inexperienced person will go into an auditorium, clap his hands, and on hearing an echo will conclude at once that the room is acoustically unsatisfactory. It is quite possible to find locations in the seating area of even an acoustically well-designed auditorium where echoes can be detected by hand claps—particularly flutters between untreated parallel side walls. In the usual type of auditorium in which the sound originates on the stage, this is not a fair test, since only those echoes or flutters which can be heard when the sound source is in its normal position on the stage can have any effect on hearing conditions.

In testing a room, one person should stand at various locations on the stage and create short, sharp sounds typical of those which would be most likely to produce echoes during the normal use of the room (such as sharply accented syllables of speech, or the sound of tap dancing or drumming). Meanwhile, a second person

should explore all parts of the seating area, facing the stage at all times, and listen for echoes. At the same time, the person on the stage should note whether his voice is thrown back at him from the rear of the room to any objectionable degree. If the room passes this test, then it should be considered satisfactory from the standpoint of echoes, regardless of whether or not echoes can be heard when the source is not on the stage. In certain types of room such as parliamentary chambers, where speeches are often made from the floor, it is necessary to test for echoes when the sound source is at various points in the seating area.

INTERFERING NOISE

While it is quite obvious that it is harder to understand a speaker in a noisy room than in a quiet room, the extent to which interfering noise affects hearing conditions is not generally appreciated. This is due partly to our having become so accustomed to various types of noise in an auditorium that we are not ordinarily aware of it, and also to the fact that, as shown by articulation tests, a steady noise level may be considerably lower than the level of speech in a room, but will nevertheless cause a serious loss of intelligibility. As far as possible, the average noise level should be kept below 30 db. in order to minimize its interfering effect.

Sources of Noise and Remedial Measures

Noise may enter an auditorium from outside the building, from adjoining rooms in the building, from mechanical and ventilating equipment, and from the audience itself.

Unavoidable outside noise such as street traffic is best controlled by means of adequate sound insulating and vibration isolating building construction. Interference from other activities in the building, as of a bowling alley or a dancing school, should be avoided where possible by locating the disturbing spaces as far away from the auditorium as possible, or otherwise guarded against by proper sound insulating construction.

Disturbance in the rear of an auditorium is often caused by commotion in adjoining foyers and lobbies. Unless adequate rear doors can be provided and kept closed, the interference can be considerably subdued by acoustically treating the lobby or foyer and providing carpeting or other resilient flooring material to quiet footsteps.

Mechanical equipment which causes building vibration and consequent noise should be isolated by suitable resilient mountings. Ventilating and air conditioning installations frequently cause an excessively high noise level. These should be quieted by avoiding high air velocities through the grilles and by the use of sound absorbent duct lining.

The audience is frequently the most serious and least controllable source of noise. Walking and shuffling of feet can, however, be successfully quieted by carpeting or resilient flooring. In low, deep under balcony spaces, where audience noise tends to build up to a higher level than in the open part of the room, acoustical treatment of the under balcony ceiling will be of considerable benefit.

Cleveland Union Terminal, Cleveland, Ohio. Noise caused by rush hour activities is now subdued by Acousti-Celotex sound-absorbing panels applied to the ceiling.

Chapter V

Acoustical Correction of Different Types of Room

IN THIS CHAPTER we shall consider the acoustical requirements of various types of audience room and the proper methods for meeting those requirements by the use of acoustical treatment. Before proceeding to the discussion of individual types of auditorium, however, a few general comments should be made.

Choice of Reverberation Time

We have seen in the last chapter how the reverberation time affects hearing conditions for speech in rooms of various sizes. In Fig. 5.1 the percentage articulation curves shown in Fig. 4.5 have been replotted to show the ranges of reverberation time over which excellent, good, fair, and poor hearing conditions for speech may be expected in any auditorium of a given size. This data refers to direct speech, and assumes a speaker of average voice power. Fig. 5.1 shows that within certain limits the reverberation time may vary over a considerable range without causing any appreciable change in the quality of hearing conditions.

For the case of speech amplified to a level of 70 db, the data of Fig. 4.8 when replotted as in Fig. 5.1 would show that the dividing lines between the excellent, good, fair, and poor zones would extend horizontally across the chart at reverberation time values of 1.9, 2.7, and 3.3 seconds, respectively, these values being independent of the room volume.

The determination of acceptable reverberation times for the hearing of music is, by the nature of the problem, less susceptible of an exact scientific procedure than is the case with speech. These determinations have therefore had to be based almost entirely on studies of existing music rooms and concert halls which possess

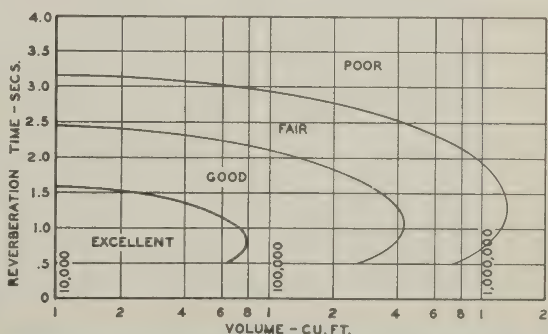


FIG. 5.1—*Quality of hearing conditions as related to reverberation time and room volume, assuming unamplified speech of average power.*

Sound Conditioning material on walls and ceiling holds noise to a low level in this large swimming pool, Beverly Hills High School, Beverly Hills, California.

established reputations for acoustical excellence for music. It has been found that the reverberation time of such rooms, with full audience, averages around 1 second for small rooms of about 5,000 cu. ft. volume, and increases with the size of the room up to about 2 seconds for volumes of 1,000,000 cu. ft. It was also found, however, that rooms of about the same size and considered to have equally good acoustics might have reverberation times differing as much as 0.4 second. This would indicate that as in the case of speech, the quality of hearing conditions for music does not depend at all critically on the reverberation time, but instead there exists a considerable range of reverberation times over which hearing conditions may be considered equally good.

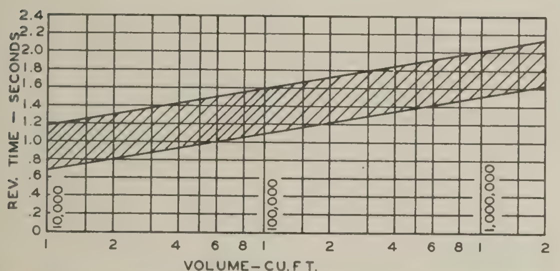


FIG. 5.2—*Range of acceptable reverberation times at a frequency of 512 cycles for auditoriums of various sizes.*

It is desirable, however, to establish some table of acceptable reverberation times for use as a guide in specifying the acoustical correction of auditoriums. Such a table has been prepared by the Technical Advisory Committee of the Acoustical Materials Association, and represents the best expert opinion on the subject at the present time. This is shown graphically in Fig. 5.2[1], in which a range of acceptable times is shown for rooms of various sizes. The values shown refer to the standard frequency 512 cycles, and are intended to apply to any type of audience room. In using this chart, it should be remembered that the reverberation time in any auditorium will vary to a considerable degree with the size of the audience. A value of acceptable reverberation time should be chosen as a design objective from within the range corresponding to the volume of the room under consideration, and sufficient acoustical treatment should be specified so that this value is obtained with the most probable size of audience present. At the same time, the correction should be sufficient to insure at least fair hearing conditions for very small audiences. In certain cases, this may necessitate lowering slightly the acceptable time originally chosen.

The choice of an acceptable time within the range shown should be governed chiefly by the use of the room. The lower part of the range applies to rooms intended for direct speech only, or for amplified speech and music. The center part of the range will insure the best results for general-purpose auditoriums in which both speech and music, either direct or amplified, may be presented. Reverberation times lying in the upper part of the range are recommended for music rooms, concert halls, and churches in which organ and choral music are emphasized.

Reverberation at Different Frequencies

All absorbing materials, including an audience, have different coefficients at different frequencies, and therefore the reverberation time of a room will vary with the frequency. It has been found by experience, however, that the reverberation time at the single frequency of 512 cycles serves in most cases as a satisfactory measure of the quality of hearing conditions. This frequency has been adopted as common practice because it is at the middle of the range of frequencies covered in acoustical measurements, and because most of the data on acceptable reverberation times have been based on this single frequency.

In most cases, absorption of the audience furnishes such a large part of the total absorption that the reverberation-frequency characteristic of an auditorium is not altered to any great extent by the introduction of acoustical treatment. However, in rooms where the treatment supplies most of the absorption, it is possible for reverberation to be excessive at other frequencies, particularly low frequencies, even though the reverberation time at 512 cycles is adjusted to the acceptable value. This excessive low-frequency reverberation, although it does not usually interfere seriously with speech intelligibility, as shown by articulation tests, nevertheless may impart a disagreeable "boomy" quality to the sound, particularly in the case of reproduced speech.

MacNair has derived a theoretical optimum reverberation-frequency characteristic based on the assumption that all frequency components of the reverberant sound should maintain the same relative loudness to each other at every stage of the decay period as is established by the original sound. This criterion leads to the charac-

[1]Taken from "Theory and Use of Architectural Acoustical Materials" published by the Acoustical Materials Association.

teristic shown in Fig. 5.3[2], which indicates that the reverberation time should be longer at the low fre-

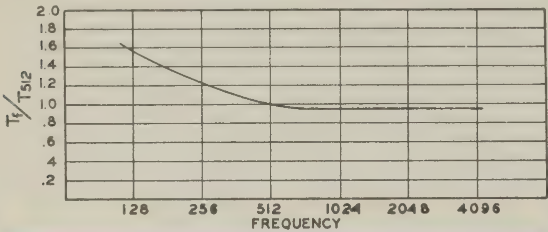


FIG. 5.3—*Optimum reverberation frequency characteristic as proposed by MacNair. Vertical scale shows the relation of reverberation time* (T_f) *at any frequency to the reverberation time* (T_{512}) *at 512 cycles.*

quencies than at 512 cycles and higher frequencies. Experience seems to indicate that reverberation-frequency characteristics approximating this curve give the most satisfactory results in large auditoriums. At least, it is the type of characteristic to which listeners are most accustomed, because it so happens that it approaches very closely the characteristic which actually exists in an acoustically untreated auditorium with a full audience. Engineers of Electrical Research Products, Inc., have observed, however, that in small rooms somewhat better quality of both speech and music is obtained if the reverberation time is approximately constant over the whole frequency range.[3]

As a general rule, adjustment of the reverberation-frequency characteristic of an auditorium should be considered in the nature of a refinement secondary in importance to the attainment of the proper reverberation time at 512 cycles.

Location and Distribution of Acoustical Treatment

It was stated in the last chapter that the Sabine formula would lead us to expect the change in reverberation time produced by the introduction of a given number of sound absorption units in the form of acoustical treatment to be the same regardless of the location or distribution of the treatment, or of whether the added absorption is supplied by a small area of high efficiency material or by a larger area of less efficient material. Fortunately, these predictions represent the facts accurately enough in the majority of cases to permit considerable flexibility in adapting acoustical treatment to the architectural design of a room.

[2]W. A. MacNair, J. Acous. Soc. Am., Vol. I, p. 242, 1930.

[3]J. P. Maxfield and C. C. Potwin, J. Acous. Soc. Am., Vol. XI, p. 390, 1940.

The choice of location of the necessary treatment will be governed to a considerable extent by the areas which happen to be available for treatment, and very often by considerations of installation cost, appearance, and harmony with the architectural treatment of the room. The ceiling is generally the most suitable surface for treatment from the architectural standpoint, and it has therefore become almost universal practice to place all of the required treatment on this surface with the attainment in general of quite satisfactory acoustical results. This does not necessarily mean that as good or better results could not be obtained by distributing the material differently. When not overruled by architectural and structural considerations, the following rules for distributing treatment should be observed:

1. In order for treatment to be fully effective in reducing the reverberation time, it must be placed on areas which are accessible to sound waves. For example, treatment placed on a low, deep under-balcony ceiling will not be as effective as the same amount of treatment placed on the main ceiling or side walls in the open part of the room. The same effect takes place in the case of other deeply recessed spaces, such as alcoves or side aisles.

2. Rear wall surfaces should be treated in any auditorium more than about 50 ft. long. It is especially important that this be done and that a highly efficient material be used if the rear wall is curved. Rear wall treatment is also of value in rooms of any size in helping to prevent acoustic feedback or "howling" in public-address systems.

3. In rooms of average proportions, it makes little practical difference whether treatment is placed on the side walls or on the ceiling, or both. In general, it is preferable in any case to distribute the material uniformly, by using either large single areas of a low or medium efficiency material or a number of smaller panels of a higher efficiency material. Unsatisfactory results may occur when it is attempted to concentrate too much absorption on too small a surface, as when the entire ceiling area of a high, narrow room is treated with a material of extremely high efficiency, all other surfaces being left untreated. In extreme cases such as this, the reverberation time may actually be considerably longer than would be expected from the formula, and the room may seem inadequately treated. The reason is that the horizontal waves which strike only the reflective

walls are absorbed much more slowly, and therefore persist longer, than those waves which strike the highly absorbent ceiling and are rapidly damped out.

4. Surfaces which furnish reflections at short enough time lags to reinforce the direct sound advantageously should be left untreated, or at most treated with low efficiency material or in partial areas. Such surfaces include low ceilings in large rooms and proscenium wall and ceiling surfaces so shaped as to direct sound at glancing angles toward the rear of the room. Absorption in the form of acoustical materials or drapes should be omitted from stage surfaces for direct speech and music. Reflective stage surfaces are of distinct benefit in increasing the loudness of a speaker's voice, and are particularly essential for music. In the latter case the support furnished by reflections not only aids each musician greatly in hearing his own instrument in the proper pitch and volume relation to the group as a whole, but also improves the blending of the ensemble for both the conductor and the audience.

Another point in connection with the distribution of absorption should be mentioned, namely, the apparent change in the efficiency of a material produced by varying the pattern. Numerous laboratory and field tests have shown that if a given area of absorbent material is arranged in small panels or narrow strips separated by reflective surfaces, the coefficient of the material is apparently greater than when the same amount of material is lumped in a single area. There is not sufficient data on this phenomenon at present to permit any general rules to be formulated. However, it has been found that the smaller the panels or strips and the wider the spacing between them, the greater will be the apparent increase in absorption coefficients. Increases ranging up to 30 percent have been measured for panels varying in size up to 2 x 8 ft. and in spacing up to 8 ft.

GENERAL PURPOSE AUDITORIUM

Method of Analysis

In order to illustrate by a concrete example the principles outlined thus far, we will go through the steps in the acoustical analysis of a typical high school auditorium. A room of this type may be used for both speech and music, either direct or reproduced, or both, and may contain audiences ranging from capacity down to a few persons, as during rehearsals. It will therefore serve as a good example of a general purpose auditorium.

We will take a room, as shown in plan and section in Fig. 5.4, having a seating capacity of 1500, a rectangular shape, a balcony, and a stage house, and will assume that it will be used under all of the conditions listed above. The main and balcony floors are of concrete, the walls and ceiling are of plaster, the seats are wood veneer opera chairs, and the stage is furnished with a heavy velour curtain and average stage hangings. The volume of this room, exclusive of the stage is approximately 260,000 cu. ft. The first step after determining the volume and the areas of the interior surfaces is to determine the total absorption in the empty room. This is done by multiplying the area of each material by its coefficient, as follows:

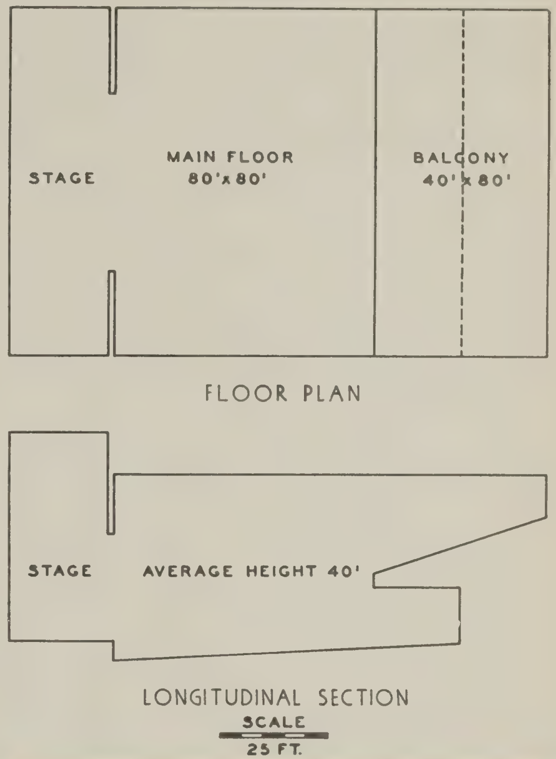


FIG. 5.4—***Plan and section of typical high school auditorium.***

Main and balcony floors, concrete	9,600 sq.ft.	@ .015	= 144 units
Ceilings, plaster	9,600 sq.ft.	@ .03	= 288 units
Walls, plaster	11,800 sq.ft.	@ .03	= 354 units
Stage curtain and opening	800 sq.ft.	@ .25	= 50 units
Grille openings	100 sq.ft.	@ .50	= 50 units
Seats, wood	1,500	@ .25	= 375 units
Miscellaneous			50 units
Total absorption in empty room			1,461 units

The coefficients shown in this tabulation have been taken from Table II in the Appendix. It will be noted that the absorption of the seats is not figured on a square foot basis, but is given as .25 units per seat. The same method is used in calculating the absorption of the audience, the commonly accepted value being 4.0 units per person. In determining the absorption added to that of the empty room by the audience, it is considered that the absorption of each seat is no longer effective when it is occupied, so that the net added absorption per person will be 4.0 units less the absorption of the seat.

In this example the volume of the stage is not included, nor the absorption of the stage floor, walls, and ceiling. The reason for this is that the stage house, being connected to the auditorium by a comparatively small opening, does not act acoustically as a part of the main volume, but instead, the stage opening acts as an absorbing surface. This is especially true when the stage curtain is drawn. As an approximation, therefore, the stage opening is considered as part of the wall area of the main auditorium and is assigned an estimated coefficient of .25 to .75, depending on the type and amount of stage furnishings. In the case of a small stage with a large opening to the auditorium, the volume and absorption of the stage should be included with that of the auditorium proper.

The 50 miscellaneous units listed above include the small amount of absorption not appearing on the blueprints or readily apparent, but which is almost always present in a room and which should be allowed for in calculation. Window hangings in a school auditorium, apparatus in a gymnasium, statuary in churches, small quantities of carpeting and drapes are often present, but not always accounted for. The absorption to be allowed is a matter of judgment for which no set rule can be given.

We will now calculate the reverberation times in the room empty, one-third full, two-thirds full, and with capacity audience, using the Sabine formula, $T = .05\ V/a$. Since one-third of the audience is 500 persons, the net added absorption will be 4.0 less .25 or 3.75 units x 500 = 1875 units for each 500 people.

$$\text{Empty Room } T = \frac{.05 \times 260{,}000}{1461} = 8.9 \text{ seconds}$$

$$\text{500 Audience } T = \frac{.05 \times 260{,}000}{1461 + (500 \times 3.75)} = 3.9 \text{ seconds}$$

$$\text{1000 Audience } T = \frac{.05 \times 260{,}000}{1461 + (1000 \times 3.75)} = 2.5 \text{ seconds}$$

$$\text{1500 Audience } T = \frac{.05 \times 260{,}000}{1461 + (1500 \times 3.75)} = 1.8 \text{ seconds}$$

By referring to Fig. 5.1 it will be seen that the reverberation time will be excessively long and hearing conditions consequently poor for any audience of less than about 500. For two-thirds capacity the reverberation time falls just within the region of "fair" hearing conditions, and with full audience the reverberation time borders on the "good" zone. If the room were to be used only with capacity audiences it could be considered quite acceptable. However, we have seen that this room is to be used for audiences of all sizes, and it will be necessary therefore to reduce the reverberation times accordingly.

Remembering that this is a general purpose auditorium, we select from Fig. 5.2 an acceptable reverberation time of 1.5 seconds, which lies near the middle of the range. Since we want to be sure of at least fairly good hearing conditions for very small audiences, it will be advisable to install enough acoustical treatment that this time is obtained with a one-third audience. We will now determine the number of absorption units required to produce this time. The Sabine formula has been given as

$$T = \frac{.05\ V}{a}$$

but it may be written as

$$a = \frac{.05\ V}{T}$$

If for T we substitute the acceptable reverberation time required, we will find the required number of absorption units,

$$a = \frac{.05 \times 260{,}000}{1.5} = 8{,}666 \text{ units}$$

We already have an absorption of 1,461 units in the empty room, and a one-third audience will furnish an additional 1,875 units, making a total of 3,336 units. Since we need 8,666 units we must add 5,330 units in the form of acoustical treatment.

Part of this treatment should be placed on the rear walls both above and below the balcony, and the remainder should be distributed on the main ceiling or side walls, or both. Since the rear wall is straight, a material of medium efficiency will be satisfactory for this surface. We will assume, therefore, that Type C-9 Acousti-Celotex Cane Tile will be used for the entire treatment. The coefficient of this material at 512 cycles is .80, but since it renders ineffective the absorption of the plaster which it covers we must subtract the coefficient of the plaster from that of the treatment and use a net coefficient of .80 — .03 = .77. The amount of this material required will be

$$\frac{5{,}330 \text{ units}}{.77} = 6{,}920 \text{ sq. ft.}$$

Applying 1,360 sq. ft. of this area to the rear walls (leaving an untreated wainscot 3 ft. high), we have a remainder of 5,560 sq. ft. to be applied on the main ceiling or side walls. The exact method of distributing this treatment should be governed chiefly by architectural considerations. Furthermore, the actual footage installed may vary plus or minus 5 percent from the calculated figure of 5,560 sq. ft., if necessary, without appreciably affecting the final acoustical results.

We will assume, however, that exactly 5,330 additional units have been installed, which added to the 1,461 units already present makes a total of 6,791 units in the empty room after treatment. Repeating the calculation as above we obtain reverberation times as follows:

$$\text{Empty Room } T = \frac{.05 \times 260{,}000}{6{,}791} = 1.9 \text{ seconds}$$

$$\text{500 Audience } T = \frac{.05 \times 260{,}000}{6791 + (500 \times 3.75)} = 1.5 \text{ seconds}$$

$$\text{1000 Audience } T = \frac{.05 \times 260{,}000}{6791 + (1000 \times 3.75)} = 1.2 \text{ seconds}$$

$$\text{1500 Audience } T = \frac{.05 \times 260{,}000}{6791 + (1500 \times 3.75)} = 1.0 \text{ seconds}$$

The above values show that the acceptable time of 1.5 seconds is reached with a one-third audience, as was desired, and reference to Fig. 5.1 indicates that hearing conditions for direct speech, assuming average voice power, will be "good" for audiences of any size greater than about 300, and "fair" for all smaller audiences. The room is too large to permit "excellent" hearing conditions for direct speech, regardless of the audience size, and hearing might be only fair or poor with a weak voiced speaker. A public address system would therefore be of considerable value. On the whole, however, this room may be considered to be acoustically satisfactory and can be used effectively for all of the purposes intended.

Effect of Upholstered Seats

The reverberation times calculated above are shown graphically in the solid curves of Fig. 5.5. If instead of

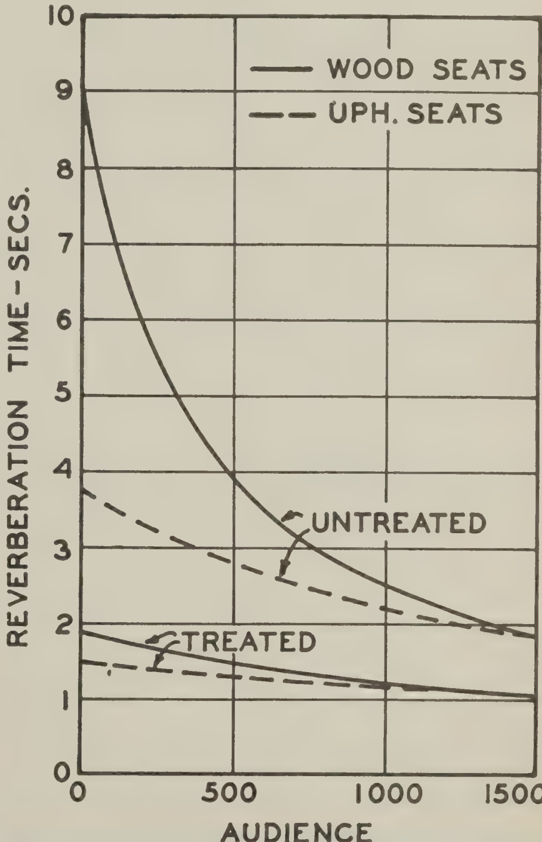


FIG. 5.5—*Variation of reverberation time with size of audience, showing effect of acoustical treatment and effect of upholstered seats.*

Auditorium of Carlisle Boro High School, Carlisle, Pa. Acousti-Celotex cane fibre tile was applied to entire ceiling area, rear wall and under balcony.

a plain wood veneer seat this auditorium had been furnished with leatherette upholstered seats having an absorption of 1.6 units each, the reverberation times in the empty room both before and after treatment would have been lower, but the change in reverberation produced by the audience would have been less, since each person occupying an upholstered seat would furnish a net absorption of $4.0 - 1.6 = 2.4$ units instead of 3.75 units. This is shown by the dotted curves of Fig. 5.5. It is seen that upholstered seats are of value acoustically both in lowering the reverberation time for small audiences and in maintaining acoustical conditions more nearly constant with respect to changes in audience size. This is particularly important in rooms where the seating capacity is large in comparison to the room volume, in which case the reverberation time would tend to vary quite markedly with changes in the size of audience.

MOTION PICTURE THEATRES

The provision of good acoustics in sound motion picture theatres is essentially a matter of transmitting the sound from the screen to the audience with a minimum of distraction and distortion due to sound reflections. This means that reverberation and echoes must be controlled to the point where they cause no appreciable loss of intelligibility nor intrude on the listener's atten-

tion.[4] It should be noted that there is no limitation on hearing conditions due to loudness, since it is a simple matter, with present high quality equipment and installation technique, to project high fidelity sound of ample loudness to every seat in the house.

Reverberation Time

The reverberation time should therefore be brought as low as is necessary to insure maximum speech intelligibility, but not so low as to make the theatre uncomfortably dead. Electrical Research Products, Inc., have found that acceptable reverberation times at 512 cycles for theatres of various sizes are best represented by the curve in Fig. 5.6,[5] which, it will be noted, follows approximately the center of the range of acceptable times shown in Fig. 5.2. The correction for a theatre of a given size should be worked out so that the acceptable time given in Fig. 5.6 will be obtained with a one-third audience, thus insuring satisfactory hearing for the entire range of possible audience sizes.

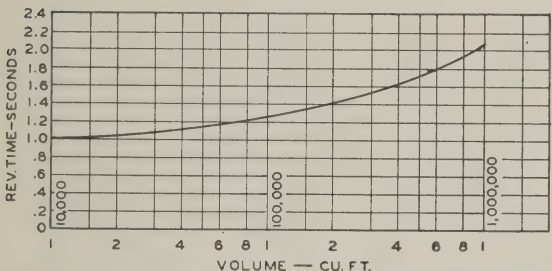


FIG. 5.6—*Optimum reverberation times at 512 cycles for talking picture theatres, as recommended by Electrical Research Products, Inc.*

Echoes and Distribution of Treatment

The control of rear wall echoes is particularly important in theatres, because of the directional properties of the loud speakers. Curved rear wall surfaces should be avoided or broken up if possible, as described in Chapter IV, and highly efficient acoustical material should be applied in any case. If the rear wall is curved, it is advisable to cover the entire wall back of the screen with a highly absorbent blanket type of material in order to prevent echoes reflected first from the rear wall of the theatre and then from the wall behind the screen. This sometimes occurs to an objectionable degree even though the rear wall of the theatre is heavily treated, as shown in Fig. 5.7. The first reflection is not noticeable because the sound waves have been mostly absorbed, because they are not sufficiently concentrated by the rear wall curvature, and because the audience's backs are turned towards them. The second reflection, however, becomes concentrated to a focal point at *F*, and due to its consequent increased loudness, to the extreme length of the time lag, and to the fact that it comes from in front of the audience, it is distinctly audible as a doubling of the original sound to the auditors in the region of the point *F*. Heavy treatment of the stage wall, as described above, is the best solution.

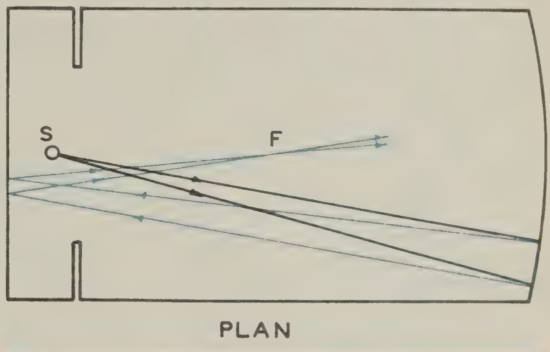


FIG. 5.7—*Diagram showing formation of focussed echoes by double reflection from curved rear wall and stage wall.*

The distribution of the remainder of the necessary acoustical treatment should be dictated to some extent by the shape of the room. In low-ceilinged rooms or long, narrow theatres of the "shooting gallery" type, treatment of evenly distributed areas on only the side walls is considered the best practice. In the case of high ceilings, treatment of at least part of the ceiling in addition to the side walls is advisable in order to minimize interference due to delayed ceiling reflections.

[4]Detailed recommendations for the acoustical design of theatres have appeared in "Theatre Acoustic Recommendations of the Academy Research Council Theatre Standardization Committee," published in the Journal of the Society of Motion Picture Engineers for March 1941. These recommendations cover the requirements for most perfect acoustical results, and impose somewhat more severe restrictions on architectural and acoustical design than are set forth by the author. It is believed, however, that the author's recommendations are not inconsistent with those of the committee, and can be expected to produce acceptable results.

[5]C. C. Potwin, "Theatre Acoustics Today," a series in *Better Theatres* magazine, May 29, 1937 to October 16, 1937, Quigley Publishing Co., New York.

Acousti-Celotex Mineral Tile applied on side and rear walls and face of balcony rail in the Uptown Theatre, Minneapolis, Minn. The mural decoration is carved in the acoustical treatment and painted with fluorescent paint for illumination by "black light." Architects, Liebenberg and Kaplan.

Frequency Characterictics

Since so much emphasis has been placed on the attainment of high fidelity sound reproduction in theatres, it has become important to insure proper reverberation-frequency characteristics, particularly the avoidance of "boom" due to insufficient absorption at low frequencies. Although, as pointed out above, the acoustical treatment can determine only partially the overall reverberation-frequency characteristic, it is advisable to choose constructions which do not exhibit wide differences in absorption at the various frequencies. Application of treatment on furring over an air space at least 2 inches deep will produce substantial increases in the low frequency absorption of most materials, and is generally recommended for theatre treatment.

CHURCHES

The acoustical requirements of a modern church are not essentially different from those of any auditorium intended for both speech and music. The success with which these requirements can be met depends to some degree, however, on the size and architectural design of the building, and on the type of service. Frequently the demands of good acoustical design are in serious contradiction to those of traditional architectural forms, so that the best possible compromise has to be worked out.[6]

[6]For an excellent discussion of church acoustics the reader is referred to *Acoustics and Architecture* by P. E. Sabine, McGraw-Hill Book Co. Inc., New York.

Size, Shape, and Loudness

The small church having a moderate ceiling height and a simple rectangular floor plan which is not excessively long in comparison to the width is the best type of design from the acoustical standpoint. Due to the small size and regular shape of the room, the loudness of direct speech will be well distributed at ample volume over all parts of the seating area. For the same reason, the value of the reverberation time is not critical, and entirely satisfactory hearing conditions may generally be expected, provided the reverberation is not excessive, as shown in Fig. 5.1.

In the Gothic type of building, characterized by a long, narrow floor plan, extremely high ceiling, and more or less deep transepts and chancel, conditions are less favorable to good hearing. The pulpit is usually placed where there are no nearby reflecting surfaces to furnish sound reinforcement. The extreme length of the seating area requires that the speaker expend more voice power in order to reach the rear seats than would be necessary if the same number of seats were placed on a shorter and wider floor plan. Finally, the ceiling and rear wall surfaces are so located as to produce reflections to a considerable part of the seating area which are so long delayed that they tend to blur rather than reinforce the direct sound. This explains the frequent complaint that hearing in churches of this type is least satisfactory in the region about one-third to one-half the way back from the pulpit. At points closer to the pulpit, the direct sound is loud enough to overcome the interference of the delayed reflections, and at the extreme rear the reflections are less delayed, and may provide some reinforcement, particularly the reflection from the rear wall. As a rule, therefore, hearing conditions for direct speech cannot be expected to be as good in a church of this type as in one having the same seating capacity but a more regular shape.

The remarks made in Chapter IV with regard to the need for speech amplification in large auditoriums of various sizes apply in general to churches. Although a minister is commonly assumed to be a trained public speaker, there are sometimes exceptions, and the average voice power of a large number of ministers is probably not much higher than that of speakers in other types of auditoriums. Amplification is especially of value in churches of the Gothic type, due to the adverse effects of this design which were just described, and is frequently necessary for volumes as low as 200,000 cu. ft. In rooms of this type, the loudspeakers should have marked directional characteristics in order to increase substantially the ratio of direct to reflected sound and thereby help to overcome the blurring effect of delayed reflections. At the same time, enough loudspeaker units should be installed to cover the seating area adequately.

Reverberation Time

The choice of the acceptable reverberation time for a church must be carefully made, and must take into consideration the size of the church, the type of service, the average and minimum attendance, and the effect of changes in audience size on the reverberation time. Through tradition, organ and choral music, particularly of the liturgical type, has become associated with longer reverberation times than have other types of music; therefore, the reverberation time must not be shortened to the point where this characteristic quality of the music is adversely affected. At the same time, of course, it is vitally important in any modern church that speech be easily understood for all sizes of audience.

As a general rule, for churches of less than about 200,000 cu. ft. volume and having no speech amplifying system, an acceptable reverberation time selected from the upper half of the range shown in Fig. 5.2 will provide entirely satisfactory conditions for both speech and music. If the ceiling is high, or, more exactly, if the volume of the room is large in comparison with the seating capacity, the value chosen should lie near the top of the range, and for the opposite condition a time near the center of the range should be selected. In this way excessive reverberation for very small audiences can be avoided. In the absence of more specific information as to average and minimum attendance, it will be generally advisable to assign the acceptable time to a two-thirds audience.

For larger churches without speech amplification, the same rule may be followed, but at the same time it must be remembered that the larger the room and the less favorable its shape, the greater become the chances that direct speech will not be heard satisfactorily regardless

Acousti-Celotex sound-absorbing tile applied in the First Lutheran Church of Papillion, Neb.

of the reverberation time. If speech amplification is used, however, as is imperative for volumes greater than about 400,000 cu. ft., more latitude in reverberation time is permissible. In many of the larger churches the musical part of the service is given special prominence, and a somewhat longer reverberation time is desirable. For churches of this class an acceptable reverberation time at the top of the range should be used.

Distribution of Treatment

In the small, regularly shaped church, as in the general purpose auditorium, the location of the treatment is not critical. Treatment of ceiling areas alone, with either a high efficiency material in panels or a less efficient material on the entire area, will provide entirely satisfactory results and can easily be adapted architecturally to almost any style of interior.

In larger rooms, additional treatment on rear wall areas is recommended. For churches of regular shape, such treatment will be of benefit in reducing rear wall echoes, which are frequently annoying to the speaker. If speech amplification is used, rear wall treatment is particularly important. In the case of a long, narrow room with a ceiling height large in comparison to the width, such as the Gothic type described above, wall treatment is strongly recommended not only for control

of echoes but in order to render all of the treatment fully effective. Since in a church of this shape the ceiling area is small in comparison to the wall areas, an attempt to supply all of the required absorption units by ceiling treatment alone will necessitate the use of an extremely efficient material. When this is done, as explained previously in this chapter, the actual reverberation time is very liable to come out considerably longer than would be expected from the calculations, with a resulting detriment to hearing conditions. If a less efficient material is used on the ceiling, and the remainder of the required absorption is supplied by wall treatment, the sound waves travelling in the various directions will be absorbed more uniformly, and the discrepancy in reverberation time will be largely avoided. Placement of this treatment on either side or rear walls will accomplish the desired result, but rear wall treatment is generally preferable in view of the added advantage of echo control.

It is realized, of course, that it is often impossible to follow to the letter the recommendations outlined above, because of the presence of large areas occupied by wood panelling, windows, organ cases, etc. These principles will be useful, however, as a guide in the design of new buildings, and as a means for predicting the quality of hearing conditions after the acoustical treatment of existing churches.

LARGE AUDITORIUMS

The assurance of good acoustics in very large rooms such as municipal auditoriums, indoor stadia, arenas, armories, etc., demands the resources of both the acoustical and the public address engineer. Since adequate speech loudness without amplification is virtually impossible in such large rooms, it is necessary first to provide loud speakers sufficient in number and so located and directed as to project sound effectively to every seat, and then to control reverberation and echoes sufficiently to render the sound intelligible.

Since the loudness can be brought up to any desired level by amplification, the value of the reverberation time is not as critical as in the case of unamplified sound in smaller rooms. Fig. 4.8 shows that excellent speech intelligibility for properly amplified sound can be expected with reverberation times in the neighborhood of 2 seconds. In fact, it is usually uneconomical and often physically impossible to get enough absorption into a very large room to bring the reverberation time much below this value. As a general rule, Fig. 4.8 should be used as a guide in selecting reverberation times for rooms of this type.

It will usually be found necessary to place acoustical treatment on both ceiling and wall areas in order to provide the required number of absorption units. Since the walls in a room of very large volume tend to produce long-delayed reflections and echoes, it is important that the wall treatment have as high a coefficient as possible. Highly efficient wall treatment has also been found beneficial in reducing the tendency of public address systems to "howl," an effect caused by feedback of sound from the loudspeakers to the microphone.

SPEECH ROOMS

Under the heading of auditoriums intended only for speech may be listed court rooms, meeting rooms, lecture halls and class rooms. Of these, good acoustical conditions are especially important in the court room. Witnesses often speak faintly and indistinctly, speakers may frequently have their backs turned to a number of their auditors and as a rule speak from positions where they are afforded no reinforcement from nearby reflective surfaces, and there may be unduly high levels of interfering noise. In view of these unavoidable handicaps to good hearing it is particularly desirable that excessive reverberation be eliminated as an added source of difficulty.

Acceptable reverberation times for speech rooms in general should be selected from the lower half of the range shown in Fig. 5.2. Although Fig. 5.1 shows that in rooms of less than about 25,000 cu. ft. volume "excellent" hearing conditions can be expected for quite a wide range of reverberation times, it is generally advisable in small rooms to bring the reverberation time to the lowest part of the acceptable range. The extra absorption thus introduced will be of value in quieting noise which may be produced either by the audience or by outside sources and which may interfere with hearing. In class rooms, which are apt to be noisy, this additional treatment has been found to be especially beneficial in providing a quiet atmosphere conducive to attention and concentration. Treatment of the entire ceiling of the average class room with a material having

Acousti-Celotex Cane Tile applied on the ceiling of a band room. Edgerton High School, Edgerton, Wisconsin. Oppenhamer & Obel, architects.

a coefficient at 512 cycles of at least .40 is generally recommended.

MUSIC ROOMS

These may be grouped under two headings: (a) concert and recital halls, and (b) rehearsal and practice rooms. The choice of reverberation times for the former type of room was discussed at the beginning of this chapter. The importance of reflective stage surfaces for concert and recital rooms should again be stressed.

In rehearsal rooms for band, orchestra, or chorus, satisfactory acoustical conditions are vitally essential for effective instruction. The director must be able to hear clearly the individual instruments or voices in order to locate and correct faults, and at the same time each player must be able to hear his own tones easily above the rest of the group in order for him to benefit by the instruction. These conditions are difficult or impossible of attainment in an excessively reverberant room. In the case of band rehearsals, furthermore, the volume of sound in a small, non-absorbent room may frequently build up to a deafening, nerve-racking level.

Although no exact data has been obtained on the best reverberation times for rehearsal rooms, experience indicates that values of .75 to 1.2 seconds for the empty room give best results for band and orchestra rooms.

Treatment of the entire ceiling with a material having a coefficient of at least .60 at 512 cycles is suitable for the band room of average ceiling height, although the use of a less efficient material on the ceiling, with the remainder of the required absorption on the walls provides somewhat better conditions. Choral rooms may have reverberation times, with no occupants, of 1.0 to 1.5 seconds.

Small practice rooms or cubicles should be treated sufficiently to prevent the sound in them from building up to an uncomfortably high level. The use of a material with a 512 cycle coefficient of .40 or more on the ceiling and on part of the available wall areas will insure satisfactory results.

BROADCASTING AND RECORDING STUDIOS

The acoustical design of radio and recording studios requires attention to a number of factors. First of all, unwanted sound such as building vibration, street noise, ventilating noise, programs in adjoining rooms, etc., must be kept at a sufficiently low level at the microphone to avoid noticeable interference with the desired sound. Secondly, the acoustical characteristics of the studio must afford a comfortable and reasonably natural auditory environment for the artists, and at the same time insure a quality of sound as reproduced by the loudspeaker which is satisfactory and pleasing to the studio engineer, the program director or producer, and the final radio audience. It is important to remember the following points in considering the latter requirements:

1. Reflected and reverberant sound has a distinctly different quality and is more prominent when listened to through a loudspeaker than when heard directly in the room where it originates. The same effect is observed, and for much the same reasons, when one listens outdoors at some distance from an open window to sound produced in the room from which the window opens.

2. As in any room, the sound entering the microphone is a combination of that which is directly transmitted from the source and that which is generally reflected by the room surfaces. The intensity of the former, as picked up by the microphone and heard through a loudspeaker in another room, depends only on the distance of the microphone from the source, while the intensity of the latter depends (approximately) only on the number of absorption units in the room and is therefore independent of microphone placement. A non-directional microphone is assumed in the foregoing statements.

It is obvious that the reflected sound, either steady state or reverberant, can be made more or less prominent in relation to the direct sound simply by varying the distance of the microphone from the source. This effect is shown graphically in Fig. 5.8 for various amounts of room absorption. Since large studios contain more absorption units than small ones, the family of curves can be taken to illustrate roughly the effect of room size on the ratio of direct to reflected sound for various microphone distances. It will be seen for example that, as would be expected, in order to maintain a given ratio of direct to reflected sound it is necessary to place the microphone much closer to the source in a small studio than in a large one.

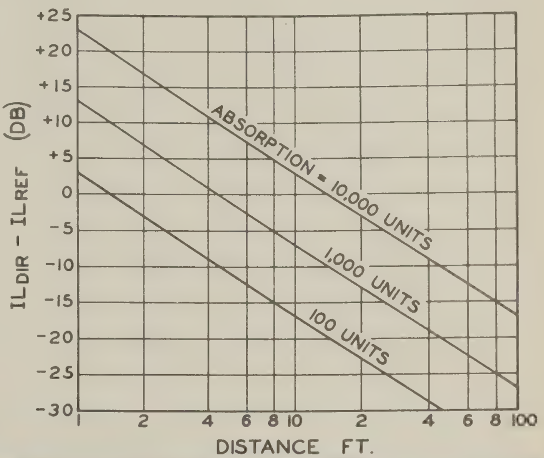


FIG. 5.8—*Level of direct sound (IL_{dir}) above or below generally reflected sound (IL_{ref}) in relation to distance from source and number of absorption units in the room.*

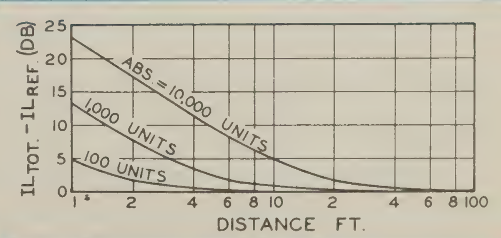


FIG. 5.9—*Level of combined direct and reflected sound (IL_{tot}) above reflected sound alone (IL_{ref}) in relation to distance from source and number of absorption units in the room.*

The same curves can be replotted as in Fig. 5.9 to show the effects of microphone distance and room absorption on the combined direct and reflected sound energy at the microphone. It can be seen that the range of microphone distances over which the microphone output depends critically on distance is greater for large or highly absorbent rooms than for small or less absorbent rooms. The data in these two charts assumes the use of a nondirectional microphone. Directional microphones tend to suppress reflected sound in relation to sound arriving directly from the source at which they are aimed, and therefore are similar in effect to increasing room size or absorption.

Layout and Design

Recommendations for the ideal layout of a group of studios and associated rooms have been given by engineers of the National Broadcasting Company[7]. In brief these recommendations call for the provision of an individual control booth for each studio and the grouping of studios around a main control room. Where space limitations permit only one control room, this should be located so as to give direct observation into every studio as far as possible.

To minimize noise transmission problems, studios should be separated from outside walls containing windows by corridors or other rooms, and should be located as far away as possible from noisy spaces such as offices, air conditioning machine rooms, etc. Studios should be separated from each other by control rooms or corridors when possible, and each studio should be furnished with a small, acoustically treated entrance vestibule or "sound lock".

Where there is a possibility of undesired sound transmission through partitions, they should be constructed to have a transmission loss of at least 45 db, and preferably 50 to 60 db. Doors and observation windows should have efficiencies of the same order as the partitions in which they are placed. Details and ratings of suitable constructions are given in Chapter VII. When the studio must occupy a space containing outside windows it is best to fill these in to eliminate interference from external noise, and provide for artificial light and ventilation. Absorbent lined ducts laid out to form long paths between rooms, silent types of grilles, and low air velocities will successfully control noise problems connected with the air conditioning system. Noise interference due to structural vibration may be a serious problem. The best results are obtained by thoroughly isolating machines or other sources of vibration from the building structure. When this is impossible it is necessary to employ floating construction in the individual studios.

The proper size of a studio is governed chiefly by the total number of persons expected to occupy it in normal use. The recommendations of the National Broadcasting Company[8] are given in Fig. 5.10, which shows the optimum relation between the volume of a studio and the number of artists (dotted line). The curve is based on experience in the use of studios of different sizes. The upper curve, marked "maximum occupancy" refers to studios where audiences are admitted.

The heighth, width, and length are shown in Fig. 5.10 in the respective proportions of 2-3-5. These approximate

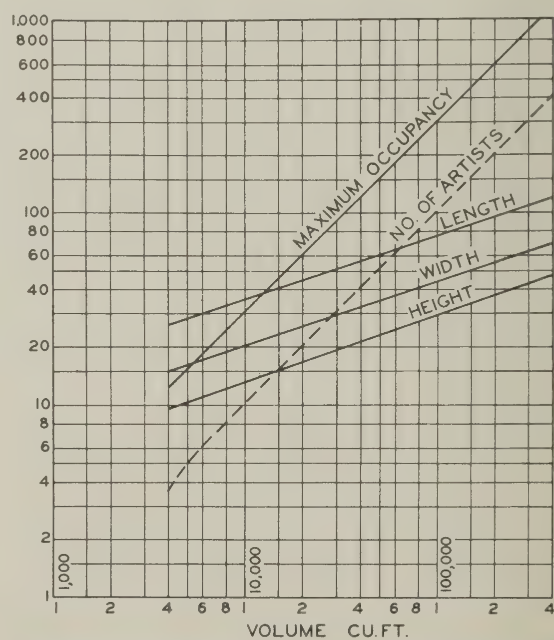


FIG. 5.10—***Relation of studio volume and dimensions to number of occupants.***

[7]R. M. Morris and G. M. Nixon, J. Acous. Soc. Am., Vol. 8, p. 81, 1936.

[8]H. M. Gurin and G. M. Nixon, J. Acous. Soc. Am., Vol. 19, p. 404, May, 1947.

Acousti-Celotex sound-absorbing tile used in the studio of Radio Station WCLT, located in Newark, Ohio.

ratios are considered preferable but are by no means critical. Proportions based on the cube root of 2, or multiples thereof, have also been recommended on the reasoning that resonance peaks observable in small rooms at low frequencies, which occur whenever the frequency is such that one of the room dimensions is equal to an integral number of half wave lengths, will be most evenly spaced and the frequency response of the room will be correspondingly smoothed. It has been shown more recently, however, that it is only in very small rooms, such as speech studios, and at low frequencies as of a low pitched male voice, that the room proportions can have any appreciable effect on the smoothness of the room frequency response, and then it is only necessary as a practical matter to avoid dimensions which are exactly commensurate, such as 1 to 1, 2 to 1, etc., to insure against any exaggerated room resonance effects. Announcers' booths and speech studios should be as large as possible, preferably not less than 10 feet in either floor dimension, so that the fundamental room resonance frequencies will be brought well below the speech frequencies and so that resonance problems together with the need for heavy acoustical treatment and close talking at the microphone will be minimized.

A generally rectangular shape is desirable for studios. Large concave surfaces should never be used, as they tend to cause focussing action and consequent uneven distribution of sound energy. In laying out walls, care

should be taken to avoid placing large plane sound-reflecting surfaces, such as doors or windows, opposite and parallel to each other. If both the sound source and the microphone happen to be placed on the same perpendicular line joining such surfaces, a multiple echo or "flutter" will be set up between them, and will be picked up by the microphone. If such a location of reflecting surfaces is unavoidable, the possibility of flutter may be minimized by draping windows or by setting the glass at a slight angle so as to put it out of parallel with the opposite surface.

Diffusive Designs

In recent years much interest has been shown in room designs involving large irregularities in wall and ceiling surfaces introduced for the purpose of producing scattered rather than regular reflection of sound waves, and consequently securing a more nearly diffuse distribution of sound energy in the room than can be obtained with completely flat surfaces. At the present writing, these irregularities have usually taken the architectural form of cylindrical and spherical segments of varying curvature and chord (known respectively as "polycylindrical diffusers" and "diffusispheres," and prismatic contours. For the purpose intended, however, an irregularity or protrusion of any architectural design may be used, provided its dimensions both in elevation and profile are of the same order as the wave lengths of the sounds for which diffusing action is desired. The elements currently used project out only about a foot or less, and therefore have negligible diffusing effect on frequencies below 200 or 300 cycles. Protrusions or recesses several feet in depth would be required for diffusion in the low frequency range.

Sloping walls and non-rectangular floor plans are sometimes suggested as diffusing agencies. These afford no appreciable scattering of reflected sound, and about their only real effect is the prevention of flutter through the elimination of parallel surfaces.

The primary physical effect of diffusion is a lessening of the interference effects caused by the interaction of reflected waves, as explained in Chapter IV. This is observable both as a reduced fluctuation in intensity from point to point, when a pure tone of fixed frequency is sounding continuously, and as a decreased variation in intensity at a fixed position when the frequency of a pure tone of constant output is varied. It has also been determined instrumentally that the decay curve of reverberant sound is smoother. The relation of this smoothing of the interference pattern due to diffusion to changes in the subjective quality of speech and music as heard directly in the studio or by microphone pickup has not as yet been clearly demonstrated. It has been found by experience, however, that somewhat higher reverberation times are tolerable, or even desirable, for musical programs in diffusive studios than in conventional studios of the same size, and also that problems of microphone placement and grouping of ensembles to secure proper balance are considerably simplified. The latter effect probably results directly from the use of higher reverberation times, rather than from diffusion itself, for the reason that the correspondingly decreased number of absorption units in the room permits a higher level of generally reflected sound at the microphone in relation to the directly transmitted sound. This means, as pointed out above, that the total sound energy at the microphone due to any one source or instrument will depend less critically on microphone distance.

Diffusing elements have thus far been constructed either of hard plaster or of plywood. The latter material is usually bent over curved wood ribs into cylindrical surfaces, and when sufficiently thin it exhibits appreciable sound absorbing efficiency due to the diaphragmatic vibration of the plywood in whole panels and segmentally. The amount of absorption and its frequency characteristics depends in a rather complex manner on the weight and stiffness of the plywood, its internal frictional resistance to bending under the action of sound waves, and on the dimensions of the air spaces formed by the ribs. It is necessary to make the spacing of the ribs non-uniform in order to stagger the resonant frequencies and the corresponding absorption peaks of the individual panels formed by the ribs, and thus obtain on the average a more uniform frequency characteristic from the entire treatment. Averaged absorption coefficients for two types of plywood construction, derived from reverberation measurements in several completed studios,[9] are shown in Fig. 5.11. Data on flat plywood panels with various mountings has recently appeared.[10]

It is seen from these curves that the average absorption is comparatively low, and in practice it is necessary to

[9] C. P. Boner, C. R. Rutherford, and C. F. Seay Jr., "Absorption Frequency Characteristics of Cylindrical Plywood," presented at the thirty-second meeting of the Acoustical Society of America, November 15, 1946.

[10] P. E. Sabine and L. G. Ramer, J. Acous. Soc. Am., Vol. 20, p. 267, May, 1948.

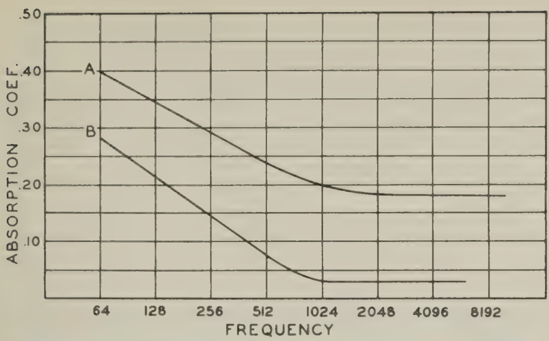


FIG. 5.11—*Averaged absorption coefficients of plywood cylinders computed from reverberation measurements in completed studios. (A) Two layers of 1/8" plywood spot cemented together. (B) Single layer of 3/8" plywood steam bent. Data obtained by C. P. Boner.*

supplement the plywood treatment with areas of standard high efficiency acoustical materials in order to provide enough absorption to secure the proper reverberation time. These areas may be applied on flat ceiling surfaces, or in strips between diffusing elements. Fig. 5.11 also shows that the plywood has more absorption at the low than at the high frequencies. By using supplementary acoustical materials which have the opposite characteristic, such as ½-inch to 1-inch tiles cemented to a solid backing, it is possible to secure overall reverberation-frequency characteristics which are substantially flat over a very wide range. A good example of such a curve, as measured in a finished studio[11], is shown in Fig. 5.12.

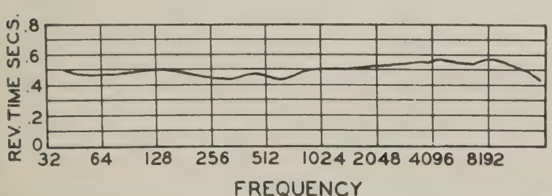


FIG. 5.12—*Measured reverberation-frequency characteristics of studio of 5650 cu. ft. volume containing curved plywood panels and conventional acoustical materials. Measurements made by C. P. Boner.*

The main disadvantage in the use of plywood for diffusing surfaces are the need for detailed construction layouts and close supervision to secure the desired absorption characteristics, and, at the present writing at least, the lack of data and the consequent uncertainty as to the total amount of absorption to be expected from a given installation. Pending more complete data, it has usually been necessary to "trim" a studio to the desired reverberation by adjusting the areas of high efficiency material.

The use of hard plaster diffusers eliminates these difficulties and permits more variety in architectural design. Since the diffusing surfaces are virtually nonabsorbent, the reverberation must be controlled almost entirely by high efficiency acoustical treatment placed on available flat areas in larger amounts than would be required if the diffusers were partially absorbent. Since the reverberation-frequency characteristic is likewise controlled by the treatment alone, special materials and constructions must be used in order to obtain the desired curve, as will be discussed in a later section.

A common misconception as to the function of diffusive designs is revealed by statements that satisfactory acoustical conditions in studios can be obtained by diffusion alone *in place of* sound absorption. Possibly this conclusion has been mistakenly drawn from either or both of the facts stated above, namely: (1) if the diffusing surfaces, as in the case of thin plywood, possess some sound absorbing efficiency in themselves, correspondingly small areas of supplementary acoustical material are required to obtain a given reverberation time; (2) somewhat higher reverberation times may be preferable when diffusion is employed. It can be easily seen, however, that diffusion *in itself* cannot affect the reverberation time of a room, when it is remembered that surface irregularities only "mix up" the sound waves and cannot remove sound energy from the room. Control of reverberation in a closed room can be effected only through the transformation of sound energy into heat energy by absorption.

Distribution of Treatment

For the general purpose studio having a regular rectangular shape and no diffusing elements, the treatment should be more or less evenly distributed on all wall and ceiling areas. If this is not done, and the entire treatment is placed on one surface, such as the ceiling, the other surfaces are necessarily left highly reflective and are liable to set up flutter echoes, as explained above. In general, it is desirable, both from an acoustical and decorative standpoint, to choose a material or com-

[11]C. P. Boner, J. Acous. Soc. Am., Vol. 13, p. 244, January, 1942.

bination of materials having coefficients such that as much as possible of the available wall and ceiling area is treated. Such surfaces as wainscots, narrow pilasters, coves, and small ceiling beams may, however, be left untreated as may be required by the architectural scheme, since they are usually of small enough size or so located as to cause no acoustical difficulties.

When diffusion is employed, absorptive and diffusive areas should be alternated as far as possible on all wall and ceiling surfaces.

The use of variable absorption in studios for adjusting acoustical conditions to differing program requirements is considered good practice. This may be provided by reversible or movable panels, or more simply by drapery which can be drawn to cover reflective surfaces, the latter preferably being shaped with diffusive contours. When hung close to the wall, drapes have high absorption only at the high frequencies and thus may be used to vary the reverberation frequency characteristic of the studio. Rugs and carpets have similar properties. By spacing the drapes a foot or so from the wall their low frequency absorption is raised to provide a flatter absorption curve and thus permit an overall adjustment of the room absorption.

Reverberation Time

The value of the correct reverberation time for a given studio is subject to a certain difference of opinion among equally qualified authorities. Any listing of "optimum" reverberation times, therefore, must be considered simply as a design objective representing, on the average, studios which have already been accepted generally as acoustically good. The same interpretation must be given to tables of the optimum relation between reverberation times over the frequency range, over which even wider divergence of opinion is encountered. In using such tables, it should be remembered that some tolerance is allowable, and that definitely unsatisfactory conditions will result only from wide departures from the listed values.

The recommendations of NBC with regard to reverberation times in studios of different volumes are shown in Fig. 5.13, which is drawn for a frequency of 512 cycles, and, except for large audience studios, refers to the empty room condition. It has been found that a single set of values, as shown, will cover most types of program, since those programs which require the longest reverberation times, such as an orchestra broadcast, also require the largest studios to accomodate the artists.

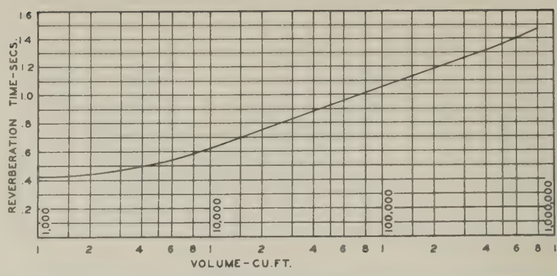


FIG. 5.13—*Optimum reverberation time at 512 cycle for studios, as recommended by National Broadcasting Company (Original NBC data given for 1000 cycles.)*

For audience studios, the times shown in the chart should be obtained with a normal sized audience present. At the same time, such studios should be furnished with heavily upholstered seats so that the empty room time will not differ too greatly from the time with the average audience.

As stated previously, there is a growing preference for considerably higher reverberation times for music than those shown in Fig. 5.13 when thorough diffusion is incorporated in the studio design.

Fig. 5.14 shows the ideal relation between reverberation time and frequency as recommended by NBC[12]. This curve shows the ratio of the optimum reverberation time at each frequency to the optimum value at 512 cycles. as determined from Fig. 5.13. This ideal relation represents the results of a study of the reverberation-frequency characteristics of studios considered satisfactory.

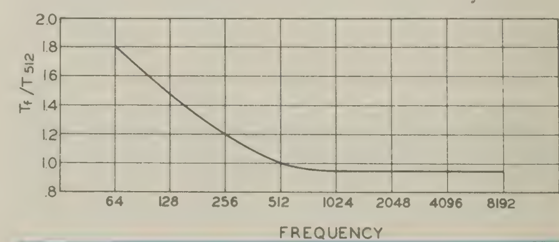


FIG. 5.14—*Optimum reverberation-frequency characteristics for studios as recommended by National Broadcasting Co. Vertical scale shows the relation of the reverberation time (T_f) at any frequency to the reverberation time (T_{512}) at 512 cycles.*

[12]George M. Nixon and John Volkmann, "Design of Recording Studios for Speech and Music", *Tele-Tech*, February, 1947.

In very small speech studios it is sometimes necessary to introduce considerably more low frequency absorption than indicated by the characteristic of Fig. 5.14 to effectively suppress low frequency resonances which are often excited by voice frequencies in small rooms. In order to secure the required low frequency absorption it may be necessary, and is quite acceptable, to provide absorption in quantities such as to bring the overall reverberation considerably below the value recommended in Fig. 5.13. For musical programs, some authorities prefer a characteristic which becomes increasingly flatter than the curve of Fig. 5.14 with decreasing studio size.

Type of Treatment

Since practically the entire absorption in a studio, except where large audiences are accomodated, is furnished by the acoustical treatment, it is necessary to choose materials and constructions having frequency characteristics such that the resulting reverberation will approximate the curve of Fig. 5.14. This requirement effectively rules out the use of thin acoustical materials applied directly to a rigid backing because of the characteristically deficient low frequency absorption of such constructions. As pointed out previously, however, this type of treatment is quite acceptable when used in combination with thin plywood having the reverse characteristic. Acoustical tiles when spaced out on furring at least two inches from the rigid backing show marked increases in low frequency absorption which give them a much more acceptable curve. (Type C-8 Acousti-Celotex over a two-inch air space is particularly recommended in this type of construction.) Perforated hardboard or asbestos board over 2 to 4 inches of mineral wool is very commonly used to provide high absorption over a wide frequency range. In this construction the frequency curve tends to become flatter with increasing thickness and density of the absorbent element. One-inch mineral wool boards spaced out 2 to 4 inches from the backing surface also show desirable frequency characteristics, the low frequency absorption increasing with the depth of the air space.

Chapter VI

Noise Reduction with Acoustical Treatment

In Chapter III it was pointed out briefly that the basic function of acoustical treatment when used for noise reduction is to eliminate, as far as possible or practical, excessive sound reflection and the annoyance and distraction which it creates. We now proceed to a more detailed discussion of how this is accomplished. It must be borne in mind, however, that the effects of absorption in reducing the annoyance of noise are not as susceptible of evaluation in precise numerical terms as is the case with the correction of hearing conditions in auditoriums. This is true for two reasons: first, it has not yet been possible to devise a numerical scale by which changes in *comfort,* or its inverse, *annoyance,* may be related directly to the physical changes produced in the sound field in a room by the introduction of absorption; second, in many cases, rooms where absorption is used for noise reduction depart so widely in size, shape, quantity and distribution of absorption, and in type and disposition of sound sources from the conditions typical of auditoriums, that existing theory is often inadequate to predict accurately the behavior of sound and the effects of absorption in such rooms. For these reasons, successful practice in the use of absorption for noise reduction has had to be built largely on wide experience guided by existing theory where applicable.

Direct and Reflected Sound

When sound is set up in a room by a single steady source of given acoustic power output, the total intensity at any point in the room may be considered to be the sum of the intensity of the direct sound and that of the generally reflected sound. The *direct sound intensity* depends only on the *distance* of the point of observation from the source, decreasing with the square of the distance.[1] It is not affected by any characteristics of the room whatever, since the directly transmitted sound does not encounter any room surfaces, and it therefore has the same intensity at a given distance that it would have in the open air with the room entirely removed.

Under certain conditions, given below, the intensity of the generally reflected sound due to the same source is the same at every point in the room, regardless of distance from the source. The *reflected sound intensity* is inversely proportional to the *total number of sound absorption units* in the room, and depends on no other room factor such as size or shape.

[1]The intensity of the direct sound at a distance D feet from a source of E watts acoustic power output is

$$I_{\text{dir.}} = \frac{8.56\,E}{D^2} \times 10^{-5}$$

The intensity level of the direct sound in decibels is

$$I.L._{\text{dir.}} = 10 \log_{10} \frac{8.56\,E}{D^2} \times 10^{11}$$

To illustrate the above rules, doubling the distance from a sound source in any room would reduce the directly transmitted intensity to one-fourth, but would not change the reflected intensity. Doubling the room absorption in any room would cut the reflected intensity in half but would not affect the direct intensity.

The conditions under which the above statements regarding the reflected sound intensity are most nearly true are as follows:

(1) The room must have regular proportions.

(2) The absorption must be fairly evenly distributed.

(3) The total number of absorption units must be small compared with the total interior surface area; in other words, the average coefficient of all the room surfaces must be low.

When large percentages of the total room surface are heavily treated and condition (3) no longer holds, the reflected sound intensity depends on the total interior room area in addition to the total number of units in the room.[2] This takes account of the obvious fact that when the number of units becomes exactly equal to the total surface area in a room, the absorption coefficient of all surfaces necessarily becomes 100 percent, and the intensity of the reflected sound must therefore be zero regardless of what the number of units happens to be. This is shown in Fig. 6.1.

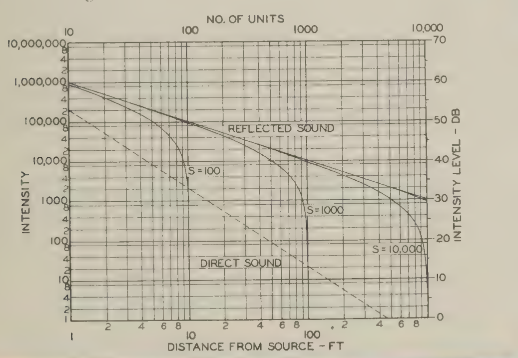


FIG. 6.1—Relation of direct sound intensity to distance from source and of reflected sound intensity to number of absorption units in room and to total room area S. Direct and reflected sound are set up by the same source.

The most frequent departure from conditions (1) and (2) above is the case of very large, low-ceilinged rooms with heavy treatment on the ceiling only, where it has been commonly observed that the reflected sound does not remain at a constant level independent of the distance from the source, but continually decreases with distance clear to the limits of the room. This drop-off of intensity takes place as a result of progressive absorption by the ceiling, its rate being governed by the height and absorption coefficient of the ceiling.[3]

The combined effects of distance and room absorption on direct, reflected, and total sound intensity due to a single steady source of power output arbitrarily chosen to produce the indicated levels is shown in Fig. 6.2, in which it is assumed that all three of the above conditions strictly hold. From this figure and from Fig. 6.1, several useful facts may be derived:

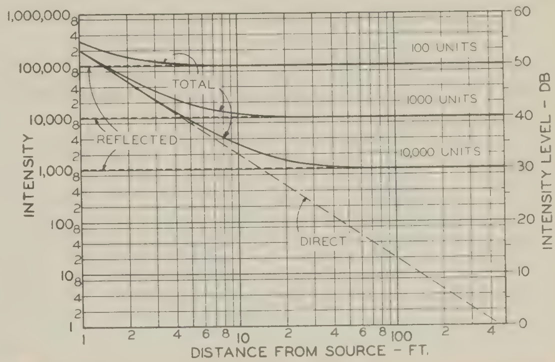


FIG. 6.2 — Curves showing relation of direct, reflected and total sound intensity to absorption in room and distance from sound source.

(1) The level of reflected sound in any room due to a given source depends (approximately) only on the number of absorption units in the room provided the number of units is less than about half of the total interior surface area. This means, for example, that of two rooms whose interior surfaces have the same low average absorption coefficient, the larger will have the lower level of reflected sound set up by a given single source, since it

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[2]The exact expression for the intensity of the reflected sound at any point in a room of S sq. ft. total interior area containing a source of E watts power output and a absorption units is

$$I_{\text{ref.}} = \frac{.00431\,E\,(1 - a/S)}{a}$$

When a is much smaller than S, that is, when the average coefficient of the interior surfaces is small, the fraction a/S is enough smaller than 1 that it can be dropped from the equation and the reflected intensity will then depend, approximately, inversely on a alone, namely,

$$I_{\text{ref.}} = \frac{.00431\,E}{a}$$

The intensity level of the reflected sound in decibels, based on the exact formula, is

$$I.L._{\text{ref.}} = 10 \log_{10} \frac{4.31\,E\,(1 - a/S) \times 10^{13}}{a}$$

A similar expression holds for the approximate formula in which the quantity $(1 - a/S)$ is dropped.

[3]H. J. Sabine and R. A. Wilson, Jour. Acous. Soc. Am., Vol. 15, p. 27, July, 1943.

will have the larger number of units. A telephone bell, for instance, will set up a higher reflected noise level in a small, bare office than in a large, bare office.

(2) As the number of units in a room is increased to more than half the total surface area, that is, as the average coefficient of all surfaces exceeds 50 percent, the intensity of reflected sound starts to fall off very rapidly, approaching zero as all surfaces approach 100 percent absorptivity. In practice, this means that extensive wall areas and possibly floor areas in addition to the ceiling must be treated with highly efficient material in order for these large decreases of reflected sound to be realized. Such large amounts of absorption are generally impractical from the structural and economic standpoints, and fortunately it is necessary to obtain such extreme reductions of reflected sound only in special test rooms, or "anechoic chambers" where accurate measurements of directly transmitted sound or noise are required.

(3) From Fig. 6.2 it can be seen that the total intensity at any point due to the combined direct and reflected sound from a single source will depend both on the distance from the source and the absorption in the room. At a point very close to the source the direct sound will furnish the largest component of the total intensity, and on moving away from the source the intensity will start to diminish. After moving farther away from the source a point will be reached where the direct sound is much less than the reflected sound, and at all distances beyond this point the total intensity will be practically equal to the reflected intensity alone, and will therefore remain essentially constant. The distance from the source at which this takes place depends only on the number of absorption units in the room.

Reverberation

Reverberation contributes to the total amount of noise energy existing in a room over a period of time, since it produces audible prolongation of noise during those intervals in which no noise energy is actually being emitted by the source. The reverberation time must therefore be considered in examining the overall characteristics of reflected sound. As has been explaind in previous chapters, the reverberation time depends directly on the room volume and inversely on the absorption in accordance with the formula $T = .05\ V/a$. It comes out that of two rooms having either the same number of absorption units or having the same average absorption coefficient, the larger room will have the longer reverberation time.

Effects of Acoustical Treatment

The benefits in increased comfort resulting from acoustical treatment of an office, a restaurant, a hospital corridor, an industrial area, or any other space having highly reflective interior surfaces and non-absorbent furnishings, are almost invariably greater than can be accounted for by the reduction of noise level alone. It has been observed many times, in fact, that the working environment of a treated room, such as an office, is preferred to that of an untreated room, even though the measured noise level in the latter may actually be lower. The reason for this is that the reduction of excessive reflection not only removes sizeable amounts of noise energy, with correspondingly lessened stimulation of the ear, but by greatly altering the time and space distribution of sound in the room it produces marked changes in the quality or character of the noise which are interpreted by the ear and brain as substantial reductions in annoyance. Based largely on study of the reactions and comments of the occupants of rooms before and after treatment, the various physical and pyschological factors involved may be analyzed as follows:

1. When any sound or noise is produced in a highly reflective room, its intensity is immediately magnified many times to a level which is interpreted by the ear as being unnaturally and unnecessarily loud, and therefore annoying. From Fig. 6.2 it can be seen, for example, that in a room containing only 100 units, as would be represented by a space 40′ x 20′ x 10′ high with reflective surfaces throughout and no absorbent furnishings, the reflected sound is louder than the direct sound even down to about 1½ feet from the source.

2. Since the intensity due to a given noise source is maintained by multiple reflection at a uniformly high level throughout the room, the noise from distant sources, such as typewriters or machines at the other end of the room, is very nearly as loud as that from nearby machines. This may be termed the *spreading effect* of noise, and constitutes a second element of annoyance in that sources far removed from the listener are heard at a loudness which is unnecessarily high in relation to their distance. The transmission of noise in untreated corridors is an excellent example of this situation. Fig. 6.2 indicates that in the room with only 100 units, sources 30 feet away are just as loud as those only 3 feet away.

3. The fact that generally reflected sound strikes the ear from many different angles at once makes it im-

Sound Conditioned corridor in the new Sacred Heart Hospital, Spokane, Washington. Acousti-Celotex tile used as ceiling finish.

possible to judge the direction and distance of the original source with normal accuracy. This together with the feeling due to the same cause of being immersed in noise very probably contributes to the sense of uneasiness and distraction so often experienced. From Fig 6.2 it can be shown that at a distance of only about 14 feet from the source, with 100 units in the room, there is 100 times as much sound energy striking the ear from directions other than that of the source than reaches the ear directly from the source.

4. When noise sources are intermittent, as typified by many machine operations and activities, the presence of excessive reverberation is responsible for a considerable degree of annoyance due to the unnecessary prolongation of an originally disagreeable noise stimulus after the original sound has stopped. In the case of short sound impulses, furthermore, the sensation of loudness depends considerably on the duration of the sound as well as on its intensity, so that an impact sound, such as the click of a typewriter or the stroke of a punch press, will seem much louder to the ear when sustained by reverberation than when the sound is cut off immediately in the absence of reverberation. It is noted in practice that in large untreated rooms the characteristically long reverberation time is frequently the most obvious feature of the general impression of noisiness. In the room of 100

Monkey House in the zoo, Buffalo, New York has been Sound Conditioned with Acousti-Celotex tile to provide a comfortable, quiet atmosphere. Architects, City of Buffalo Architectural Department.

Showroom-office of Billings Gas Company, Billings, Montana. Acousti-Celotex tile absorbs unwanted sounds and provides an attractive, light-reflecting ceiling.

units being used as an example, the calculated reverberation time is 4 seconds, indicating an excessive prolongation of noise impulses.

All of the above factors contribute in varying amounts to the overall impression of "noisiness" and confusion observed in a non-absorbent room and described by the average person as the disagreeable "ringing" or "roaring" quality of all sounds produced in such a room. In many cases, of course, some of these effects may actually interfere directly with working operations. Activities which depend on verbal or telephone communication are especially subject to disruption by the effects of reverberation and spreading both on speech sounds and on background noise which may be present. Sometimes the ability to hear and locate the sources of particular sounds accurately is an important factor in machine operation, and interference with this function by excessive sound reflection becomes serious.

After adequate acoustical treatment is installed, the intensity of all reflected sound in the room is substantially decreased. Continuing our example, and assuming that the absorption is increased from 100 to 1000 units, Fig. 6.2 shows that the reflected sound intensity created by any given source is decreased in inverse ratio, namely to one tenth of its former value.

With the accompanying reduction of the spreading effect of noise, distant sources in the room are much less apparent to the ear in relation to those nearby. With the

absorption increased to 1000 units, sources 30 feet distant are heard at only about one-third the intensity of those at 3 feet, instead of being equally loud as before. Considering the spreading effect from a different aspect, the intensity observed in moving away from a single source continues to drop off up to a distance of 15 feet with 1000 units in the room before reaching a constant level, according to Fig. 6.2, as against a distance of only 5 feet with 100 units. The impression is now that of being able to escape the noise from a given source by moving away from it, instead of having the noise "follow" one throughout of the room in the reflective condition.

It becomes much easier to judge the location of individual noise sources with increased absorption, due to the reduction of 10 to 1 in the amount of sound energy reaching the ear by reflected paths.

As a result of the tenfold reduction in reverberation time, namely 4 seconds to 0.4 seconds, all sounds are cut off sharply after they are produced, and the amount of noise audible as prolongation becomes negligible.

A person now has the impression that the noise in the room no longer immerses him but has been "pushed back" to the various individual sources producing it, and that it has a muffled, deadened quality in sharp contrast to its previous ringing, reverberant character. These changes in the quality and pervasiveness of noise combine with the loudness reduction to produce the overall quieting effect characteristic of acoustical treatment. The contrast in the character of the noise contributes very appreciably to the average person's estimate of the amount of noise reduction effected by treatment, and it is probably as much responsible as the loudness reduction, and possibly more so, for the resulting improvements in comfort and facilitation of working operations.

Consideration of all of the above effects of acoustical treatment, incidentally, has led to the general use of the term "sound conditioning". The analogy to air conditioning is apparent when it is remembered that in the latter instance comfort depends not only on cooling the air, but also on proper control of humidity and circulation.

Effects of Noise Sources

The degree of annoyance due to reflected sound and the corresponding relief afforded by acoustical treatment are governed to some extent by the type and distribution of noise sources in the room and the location of the occupants with respect to them. The most noticeable contrast brought about by treatment is obtained under conditions where the effects of reflected sound are most obvious to the ear beforehand. Thus, the factors of intermittence of noise sources, diversity of character and intensity, and wide spacing allow maximum audibility of the spreading effect, reverberation, and intensity amplification due to multiple reflection, and are therefore conducive to the best results from treatment. At the other extreme, the condition least favorable to effective correction by treatment is the presence of a multiplicity of identical, continuous, steady, closely spaced noise sources, with the listener in close proximity to one or more of them. In this case, it is difficult or impossible for the ear to differentiate the generally reflected sound from that which is transmitted directly from the nearest sources, and removal of the reflected sound by absorption is not readily noticeable. Fortunately, most situations encountered in practice tend to the more favorable combination of factors.

Required Amounts of Treatment

In determining the amount of treatment required for satisfactorily sound conditioning a given room, the problem should be considered from one of two angles, namely, whether the treatment is being built into a new, unoccupied space, or whether it is being used to correct a noisy condition in an existing, occupied room. In either case, the amount of absorption employed must be proportioned to the size and shape of the room in such a way that the effects of sound reflection, *i.e.*, intensity build-up, reverberation, and spreading, are made essentially unnoticeable to the ear, but that the extent of treatment is kept within practical and economical limits. This can be accomplished satisfactorily in the great majority of practical cases by use of the following working rule, which is based on extensive experience:

Rule 1. The total number of absorption units in any room (not including absorption of occupants) *should be between 20% and 50% of the total interior surface area.*

If the amount of treatment is much below this range, reflected sound will become disagreeably apparent in the form of reverberation in large or high-ceilinged rooms and as excessive intensity, spreading, and loss of directionality in small or low ceilinged rooms. Working out

Sound Conditioned dining room of the Elks Club, Lincoln, Nebraska.

a few examples will show that the 20% limit generally requires treatment of at least the entire ceiling, or its equivalent area, and that the 50% limit can be reached by treating all of the ceiling and at least half of the wall areas with highly efficient material. While choice of the exact amount of absorption within the 20% to 50% working range is not subject to hard and fast rules, it can be stated in a general way that the lower part of the range is suitable for rooms having floor plans large in comparison to the ceiling height and for noise sources of moderate intensity and wide spacing, while the opposite conditions require use of the upper part of the range for most satisfactory results. If the type and distribution of noise sources in a new space is not yet known or is subject to change, it would be advisable to provide for an amount of treatment lying in the upper part of the range in order to anticipate all probable conditions.

When treatment is being used to correct an existing noisy condition in an occupied space, it is important not only to arrive at a total amount of absorption lying within the range given in Rule 1, but it is especially necessary to make sure that the added absorption is sufficient to produce a satisfactory and unmistakable improvement over the previous condition, as judged by the ear. A measure of this change is provided by what may be

Sound-absorbing ceiling and upper walls of Acousti-Celotex tile make this a quiet classroom. Sunnyvale Grammar School, Calfiornia. Architect, Don Powers Smith.

termed the *absorption ratio,* a_2/a_1, where a_2 is the total number of absorption units in a given room *after* treatment, and a_1 is the number of units *before* treatment, The absorption ratio, in other words, is simply the number of times the absorption in a room is increased by treatment. A second working rule, also based on experience, may be stated as follows:

Rule 2. *To produce a satisfactory improvement in an existing room, the total absorption after treatment should be between 3 and 10 times the absorption before treatment.*

The absorption ratio of 3 is about the least which is recognized by the ear as an appreciable change in the overall effects of reflected sound under average conditions, while a 10 to 1 increase in absorption in the average room corresponds to the point where sound reflection is so greatly reduced that further addition of absorption aproaches a point of diminishing return as far as the ear is concerned, and therefore tends to become uneconomical.

Rule 1 should always be used as a check on Rule 2 when considering treatment for an existing room. For example, a room before treatment might contain unusually reflective surfaces such as hard concrete and glazed tile and very few furnishings, so that the absorption would come to only 2 percent, say, of the total surface area. If the absorption were increased 10 times, in accordance with the upper limit of Rule 2, the total ab-

sorption would still be only 20 percent of the room area, which is the lower limit for the required absorption given by rule 1. In such a case it would probably be advisable to increase the absorption by more than 10 times, which in view of the very small amount of original absorption would not involve an excessive amount of treatment. This would bring the total absorption farther within the range of 20 to 50 percent of the room area with a correspondingly more satisfactory reduction of sound reflection. The contrast between the before and after conditions would be greater than usual, but only because the "before" condition was so much worse than usual due to the abnormally low original absorption.

Calculating Noise Reduction

General methods of arriving at numerical estimates of the effects of acoustical treatment graphically or by computation have been indicated in the foregoing discussion. It must be pointed out once more that the accuracy of such calculations as an index of actual acoustical conditions depends on how closely the assumptions on which the theory is based are approximated in the particular room under consideration. Thus, the room used in the foregoing example, having dimensions of 40′ x 20′ x 10′, with absorptions of 100 units and 1000 units before and after treatment, respectively, would have sufficiently regular proportions and a low enough average absorption coefficient, even after treatment, that calculations of reflected intensity reduction, reverberation, and spreading would agree reasonably well with actual measurements. In a room, however, of the order of 100 ft. or more in each floor dimension, with only a 10 or 15 foot ceiling height, the distribution of sound energy would differ so far from the uniform, diffuse condition assumed in the theory, especially with the entire ceiling heavily treated, that the results of calculations would have very little physical meaning.

The most usual type of calculation is the comparison of conditions in an existing room before and after treatment. In predicting the reduction of reflected sound, furthermore it is usually of more interest and practical utility to express the result in terms of *loudness reduction*, rather than as an intensity reduction. It will be remembered from Chapter I that a given percentage change in physical intensity is interpreted by the ear as a somewhat smaller percentage change in the sensation of loudness. Thus, for example, a 90 percent reduction in the intensity of a sound will be judged by the average ear as about a 50 percent reduction in loudness. The actual relation of loudness changes to intensity changes varies somewhat with the initial intensity itself and with the frequency composition of the sound, but a single curve representing average condition will serve as a satisfactory approximation for practical purposes. If it is further assumed that the room proportions and distribution of treatment are such that the intensity of the reflected sound is uniform throughout the room and inversely proportional to the number of absorption units, then a chart can be drawn as in Fig. 6.3 by means of which the percentage loudness reduction of the reflected sound can be determined directly from the absorption ratio a_2/a_1. For example, if the absorption in a room were increased five times by treatment ($a_2/a_1=5$) the intensity of the reflected sound would be reduced to one-fifth of its previous value, that is, by 80 percent. The *loudness* of the reflected sound, as heard by the ear, would be found from Fig. 6.3 to be reduced by 42 percent.

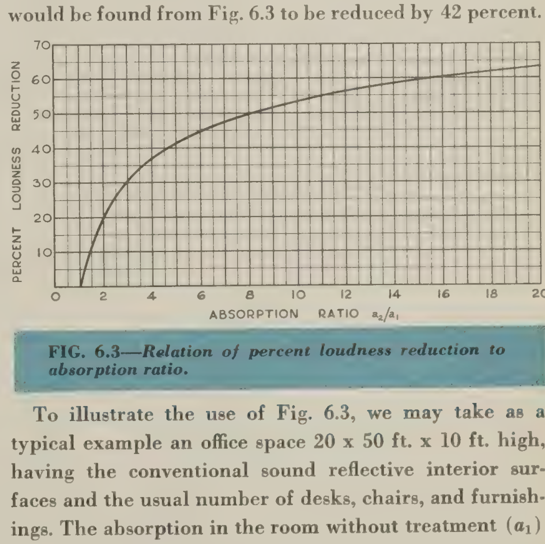


FIG. 6.3—*Relation of percent loudness reduction to absorption ratio.*

To illustrate the use of Fig. 6.3, we may take as a typical example an office space 20 x 50 ft. x 10 ft. high, having the conventional sound reflective interior surfaces and the usual number of desks, chairs, and furnishings. The absorption in the room without treatment (a_1) is determined in the same manner as in the acoustical analysis of an auditorium, namely,

Floor, linoleum	1000 sq. ft.	@ .03	= 30 units
Ceiling, plaster	1000 sq. ft.	@ .03	= 30 units
Walls, plaster	1400 sq. ft.	@ .03	= 42 units
Desks	15	@ 1.0	= 15 units
Chairs	15	@ .2	= 3 units
Miscellaneous			5 units
Total absorption before treatment (a_1) ..			125 units

We will assume that the entire ceiling area is to be treated with Type C-9 Acousti-Celotex Cane Tile, applied on furring. The noise reduction coefficient of this material, on this mounting, is .70, and 1000 sq. ft. having a net coefficient (after subtracting .03 for the plaster covered up) of .67 will furnish 670 net added absorption units. The total absorption in the room after treatment (a_2) will then be 125 + 670 = 795 units. Dividing a_2 by a_1, we find that the absorption has been increased 6.36 times, which means that the intensity of the reflected sound has been reduced to 1/6.36 or 15.7 percent of its value before treatment. By referring to Fig. 6.3, we find that an absorption ratio (a_1/a_2) of 6.36 corresponds to a reduction in loudness of 46 percent.

By computing the volume of the room, namely, 10,000 cu. ft., and using the formula $T = .05\ V/a$, we would find that the reverberation time is reduced from 4.0 seconds, an excessively high value, to .63 seconds, which is so low as to be virtually unnoticeable to the ear. If we did not wish to calculate the actual reverberation times, we could say, knowing that the reverberation time is inversely proportional to the absorption, that the reverberation is reduced by the same factor, namely 6.36, by which the absorption is increased. A more positive way of expressing the same thing would be to state that noise energy dies out, after its source is stopped, 6.36 times as fast after treatment as before.

The reduction in spreading effect can be estimated by interpolating the amounts of absorption before and after treatment (125 and 795 units, respectively) on Fig. 6.2. It will be found that the result is very similar to that shown for the previous example in the section "Effects of Acoustical Treatment".

Finally, a check of the calculations against the working rules given in the last section shows that the absorption ratio of 6.36 lies well within the range of 3 to 10 recommended in Rule 2, indicating that a satisfactory contrast with the conditions before treatment can be expected. Applying Rule 1, it is found that the total number of units after treatment (795) is 23 percent of the total room surface (3400 sq. ft.). This is near the lower limit of the recommended range of 20 to 50 percent.

If it is desired to express the reduction of reflected sound energy on the decibel scale rather than as a loudness or intensity reduction, this can be easily calculated from the formula

$$\text{Reduction, in decibels} = \log_{10} \frac{a_2}{a_1}$$

or can be read from the chart of Fig. 1.2-b simply by substituting a_2/a_1 for I_1/I_2 on the horizontal scale.

Noise Reduction Coefficient

It will be noted in the above example that the noise reduction coefficient of the acoustical material was used in calculating the absorption furnished by it. The noise reduction coefficient was defined in Chapter II as the numerical average, to the nearest 5 points, of the coefficients at the four frequencies 256, 512, 1024, and 2048 cycles. This method of rating materials was adopted by the industry on the reasoning that since the energy in most types of noise is largely contained in the frequency range between 256 and 2048 cycles, and is more or less uniformly distributed over this range, a truer comparison of the noise absorbing qualities of materials can be gained by averaging the coefficients at the four frequencies within this range than by considering the coefficient at any single frequency.

Now, if the absorption ratio is calculated for each of these four frequencies, using the actual coefficient at each frequency, it will be found that the average of these four absorption ratios is not exactly equal to the absorption ratio calculated from the average of the four coefficients, but that the agreement is close enough that the latter method of calculation provides a convenient and satisfactory approximation. Accordingly, it is now customary to use the noise reduction coefficient in calculating absorption ratios, rather than the coefficient at 512 cycles or any other single frequency.

Variation of Loudness Reduction with Absorption

The question often arises as to the gain or loss in noise quieting to be expected by increasing or decreasing the efficiency or the area of acoustical treatment. Insofar as the calculated loudness reduction is concerned, this can be answered by carrying out the calculations in the example just given for materials having noise reduction coefficients higher and lower than the .70 originally chosen, as shown in the following table.

Noise Red. Coeff.	Added units = 1000 sq. ft. x net coeff.	Units after treatment (a_2) = added units + 125 (a_1)	$\frac{a_2}{a_1}$	Loudness Reduction, percent
.40	370	495	3.96	37
.50	470	595	4.76	41
.60	570	695	5.36	44
.70	670	795	6.36	46
.80	770	895	7.16	48
.90	870	995	7.96	50

This data shows that the loudness reduction follows a law of diminishing return in that as the coefficient of the absorbing material is increased, the quieting increases by smaller and smaller amounts. For example, a material having a coefficient of .40 produces a 37 percent reduction, but a material with twice the absorption, namely .80, does not give twice the reduction but only 48 percent reduction. Similarly, increasing the coefficient from .40 to .60 produces a larger change in reduction than does an increase of the coefficient from .60 to .80. It should be remembered that the numerical values above apply only to the particular example chosen, but the effect of diminishing return is a general rule.

The data in this table can be used to show the same effect when the area of the material, instead of its coefficient, is changed. For example, an increase from 370 to 570 net added absorption units can be obtained by increasing the area of the .40 material from 1000 to 1540 sq. ft. (by additional wall treatment), with a corresponding increase in the loudness reduction from 37 to 44 percent. Addition of another 540 sq. ft. of the same material, bringing the number of added units up to 770, would increase the reduction only to 48 percent.

The shape of the curve of Fig. 6.3, together with the foregoing data, explains why it is usually not economically justifiable to increase the absorption in a room more than about 10 times (the upper limit of Rule 2) by means of treatment. If, however, it is necessary to remove larger amounts of reflected sound for special purposes it will be found that the loudness reduction of reflected sound becomes somewhat greater than indicated in Fig. 6.3 as the absorption ratio approaches 20 and will rise rapidly to 100 percent as all of the room surfaces become totally absorptive, or equivalent to free space. This effect will be made clear by reference to Fig. 6.1 and the accompanying discussion. If the average absorption coefficient of all the room surfaces before treatment were assumed to have a typical value of .03, the attainment of complete absorption by all surfaces would correspond to an absorption ratio of $33\frac{1}{3}$.

Measurement of Overall Noise Level Reduction

It is often desired to make before-and-after readings of noise level with a sound level meter to measure the effect of acoustical treatment in a given room or to compare actual results against those predicted by calculation. It will be appreciated from the foregoing discussion that conducting tests for the latter purpose with any degree of scientific precision is far from a simple procedure and requires careful attention to all factors entering into the test conditions. These may be listed as follows:

1. The room must be of regular enough proportions and of low enough average absorption, after treatment, that the assumptions on which the calculations are based are valid. A test for this condition is to find some distance from a single source beyond which the measured sound level remains constant, on the average, clear to the limits of the room.

2. Since the calculations refer only to the reflected sound, while sound level measurements record the combined direct and reflected sound, readings must be taken at distances far enough from the source that the directly transmitted component is negligible in comparison with the generally reflected level. The required distance can be estimated from Fig. 6.2, and can be checked by noting whether the level due to a single source remains constant with increasing distance. The use of a single source near one end of the room rather than distributed multiple sources will obviously make this and the foregoing condition easier to fulfill.

3. The source must of course have the same acoustic output after treatment as before. This can be checked by taking readings close enough to the source, say, 1 or 2 feet, that the reflected sound is negligible in comparison to the direct sound. An audio signal generator feeding a loud speaker, a steady, continuous noise as of a motor driven machine, or a recording of such a noise, are satisfactory sound sources from the standpoint of ease of reading and reproducibility.

4. Both the calculations and the measurements must be made at single frequencies or narrow bands of frequencies. As pointed out above, the reduction calculated from the Noise Reduction Coefficient of the acoustical material is only approximate, and may be in considerable error if the absorption-frequency characteristic of the material differs widely from the intensity-frequency distribution of a particular noise source. Narrow frequency bands are much preferable to fixed single frequencies for uniformity of readings, due to their tendency to average out the point-to-point fluctuations caused by the interference pattern, and may be obtained by "warbling" the tone of a signal generator, or by the use of band pass filters in conjunction with a complex tone or noise source.

If before-and-after measurements are made simply on a spot check basis to compare average noise levels due

Accounting and Auditing Department of Society for Savings Bank, Cleveland, Ohio. The Acousti-Celotex sound-absorbing ceiling and the modern lighting units contribute toward peak office efficiency.

to the actual noise sources normally present in the room, it will be found in general that agreement with theoretical predictions is only approximate and that measured reductions will be less than calculated values in about the degree that the test conditions listed above are not strictly complied with. In particular, it will be found, as would be logically expected, that at test positions close to a single source or in the midst of closely spaced sources, where the directly transmitted sound is large in comparison to the reflected sound, the measured effect of treatment in reducing the overall level is much less than at locations which are far enough from any single source that the reflected sound is the major component of the total energy.

It will also be found that if the noise is due to a number of varied or randomly intermittent sources, as in a machine shop, the resulting irregular fluctuations of noise level may be so much larger than the expected reduction due to the treatment that it is impossible to obtain even an approximate measured comparison of before-and-after conditions.

Adjustment of Treatment to Specific Noise Levels

The acoustical engineer is sometimes requested to make recommendations for the extent and efficiency of treatment solely on the basis of the noise levels existing or expected in the space under consideration. For instance, he may be asked to make a noise survey in a large office building and to establish various fixed ranges of noise level within which he recommends heavy, medium, light, or no treatment, respectively. This procedure is normally followed in a very approximate way in that heavy treatment is commonly recommended in small rooms containing intense noise sources, where it is generally desirable to remove as much of the total sound energy as possible. However, the consideration of noise levels alone is somewhat of an over-simplification, and does not necessarily insure the most economical and satisfactory results. The severity of the annoyance factors connected with the reverberation, spreading, and non-directionality of reflected sound and the effects of the spacing and intermittence of noise sources, depends only secondarily on the magnitude of the noise levels involved, but these factors, as well as the reflected sound level, are all controlled directly by the amount of absorption, and must all be taken into account in arriving at a recommendation for a given space.

OFFICE QUIETING

General Offices—Size, Shape, and Location of Treatment

By working out a few examples it will be found that the absorption ratio a_2/a_1, which governs the degree of noise reduction, depends approximately on the ratio of the area treated to the total area of the room surfaces. It follows, therefore, that the larger the ceiling area of an office in comparison to the ceiling height, the greater is the reduction obtainable by treating the ceiling only. A general office space of 1000 square feet or more with a 9 to 12 foot ceiling has a large enough ratio of ceiling area to ceiling height that entirely satisfactory quieting can be expected by treating the ceiling with a material having a noise reducion coefficient of .60 to .80. In very large office spaces of around 10,000 square feet, with low ceilings, treatment with a material having a coefficient as low as .50 will be quite satisfactory.

In the case of offices smaller than about 1000 square feet, or offices of about this size but with unusually high ceilings, the ratio of the ceiling area to the total interior area becomes smaller, and it is necessary to provide more absorption to secure good results. This may be done to a certain extent by treating the ceiling alone with as highly efficient a material as possible, but it is generally preferable and often necessary to furnish the required absorption by treatment of part of the wall areas in addition to the ceiling. In small rooms having floor dimensions of 20 feet or less, distribution of the required absorption on both wall and ceiling areas is particularly important. In such cases there is often a tendency for a large part of the sound energy in the room to be reflected back and forth horizontally between the walls without striking the ceiling at all. The result is that if all of the absorption in the room is concentrated on the ceiling it will not be as effective in reducing these horizontal reflections as the same amount of absorption distributed on both ceiling and wall areas, and the room will sound unduly reverberant. In general, only moderately efficient wall treatment is necessary to overcome this effect satisfactorily.

Private Offices

In the quieting of private offices by absorption a careful analysis of the conditions in individual cases is necessary. In most instances there are no very intense noise sources, such as typewriters, in the room itself. Instead, the complaint of the occupant is usually due to the gen-

Sound Conditioning maintains a low noise level in this large office of the General Insurance Company of Los Angeles. Acousti-Celotex "soaks-up" sounds before they can build up into an irritating din.

erally noisy and reverberant condition of the room resulting simply from the extremely small amount of absorption in it. Cases of this type may be successfully handled in the same manner as small general offices, with treatment installed on part of the wall areas in addition to the ceiling whenever possible.

Frequently the most serious cause of disturbance is traffic noises which enter the room through the open window. Usually the occupant of the office sits so close to the window that the noise reaching his ear cannot be reduced by absorbent treatment as effectively as if he were at the other side of the room. Under these conditions it is often necessary to supplement the acoustical treatment by the installation of sound absorbing window baffles which will ventilate the room but cut down the penetration of outside noise.

Another instance often encountered is the luxuriously furnished private office. Rooms of this type are in effect already quieted to a considerable extent by the absorption of the heavy carpet, drapes, and upholstered furniture, so that it is impossible to obtain as much additional quieting by acoustical treatment as is possible in the conventional room with no absorbent furnishings.

Machine Rooms

In most large offices the noisiest types of machines are generally crowded quite close together in a small room, and the resulting combination of high sound energy and low absorption tends to set up an extremely high noise level and consequently a difficult quieting problem. It should be realized that under such severe conditions no amount of acoustical treatment can produce as quiet or comfortable surroundings as are obtainable in a typical general office space. However, since the noise level is so high, it is important to secure as large a reduction of reflected noise as possible by treating all available wall and ceiling areas with highly efficient materials. Although the noise levels existing after such treatment may still be uncomfortably high, experience has shown that relief from the previous noise condition is very much worth while.

In cases where a separate room is not available for noisy machines, they are often grouped in a corner or wing of a large general office space, and the question is asked whether treating the ceiling and walls near the machines will cause an appreciable relief from the noise they make. In a large office with a low ceiling a localized quieting effect can be obtained in this way, the magnitude of which depends on the area and efficiency of the treatment used. In most cases the quieting effect will be very noticeable to the operators of the machines, but less so to the occupants of the untreated part of the room.

Part-Height Partitions

The division of a large office space into smaller offices by the installation of partitions less than ceiling height is a rather common practice and the question is frequently asked whether use of a highly absorbent material over the entire ceiling will give the effect of privacy acoustically. The answer in general is "no". The reason for this is easily seen when it is remembered that even if the ceiling were entirely removed, which would be equivalent to making it 100 percent sound absorbent, there would still be a considerable amount of sound which would pass over the partition and down into the next office where it could be easily heard.

Reduction of Reverberation

One point which is frequently misunderstood and may result in dissatisfaction has to do with the effect of absorption on the distinctness with which sounds may be heard. In an untreated office, the highly sound reflective surfaces, in addition to building up sound intensity to a high level, also cause excessive reverberation, which, together with the interfering effect of the noise, tend to make it difficult or impossible to understand speech except at close range. Acoustical treatment not only reduces noise but also decreases reverberation to a very low value, and these combined effects of absorption may increase the ease with which speech is understood.

This situation is usually encountered in offices which contain very few noise sources, but in which there are one or two individuals who are in the habit of talking more loudly than is necessary. A simple remedy is to scatter a few more noise sources such as typewriters throughout the room, so that their noise will tend to cover up the sound of the speech.

INDUSTRIAL QUIETING

In recent years the reduction of noise has received considerable attention as an important contribution to the comfort of industrial workers[4]. Factory noise problems in general are apt to be somewhat more complex than the situations encountered in offices, for two rea-

[4]H. J. Sabine and R. A. Wilson, "The Application of Sound Absorption to Factory Noise Problems," Jour. Acous. Soc. Am., Vol. 15, p. 27, July, 1943.

sons. In the first place, the average noise levels in industrial areas are substantially higher and frequently reach values of more than 90 decibels. At these high levels conversation becomes difficult or impossible, and pronounced physical distress in the form of temporary deafening, ringing in the ears, and nervous fatigue may be experienced. Secondly, a much wider diversity of conditions will be found. Rooms under consideration may vary in size from a small test cubicle to a huge assembly area 60 or 70 feet high and literally a mile long. Noise sources may be arranged in banks of closely spaced identical units, as in a spinning room or a screw machine department, or may be widely spaced and varied in type as in a wood or metal machine shop, a riveting or chipping department, a punch press room, or the like. These variable conditions do not invalidate the basic principles of noise reduction, but they do require critical observation and analysis of all the factors contributing to the overall discomfort due to noise in each individual situation.

Use of Acoustical Treatment

When considering the possibilities of noise reduction with acoustical treatment it is of first importance to estimate what proportion of the total noise to which a given worker or group is exposed is due to direct transmission and how much to reflection from room surfaces. Reference to Figs. 6.1 and 6.2 will be of some help, as will the judicious use of a sound level meter, but the multiplicity and variability of noise sources in a typical factory area is such that careful and experienced listening is generally necessary. It is usually possible to judge from such observations the effects of sound reflection by picturing "in the mind's ear" how the noise would be changed both in intensity and quality if the walls and ceiling of the room were completely removed. This would of course represent the limit of the effect obtainable with sound absorption. In this way it is possible to make a fair qualitative estimate of what can be accomplished by absorption and to avoid either overrating or underrating its possibilities.

Experience has shown generally that the most favorable results from acoustical treatment can be anticipated in those areas where an excessively reverberant condition is most noticeable, as in large, high ceilinged rooms containing diversified noise sources of an intermittent or impact character, such as riveters, punch presses, drop hammers, etc. Cutting down the prolongation of such sounds due to multiple reflection eliminates the roar and confusion typical of large areas.

Another condition in which treatment will be particularly effective is the audible spreading of intense noise sources originating at distant locations in an area, especially when the noise carries into comparatively quiet locations. This effect accompanies excessive reverberation, but may also be heard under conditions where reverberation is not especially noticeable, as in low ceilinged rooms with continuous noise sources.

It has been found that the rate of attenuation, or "drop-off", of noise intensity with distance in rooms of moderate ceiling height can be considerably increased by installing acoustical treatment in the form of vertical panels or baffles instead of, or in addition to, the usual ceiling treatment. These are normally installed with their lower edges just above head level, and may or may not extend all the way to the ceiling. Their function is to block the spread of sound by way of ceiling reflection, and they probably furnish some additional trapping action by the divergence and consequent attenuation of sound waves due to diffraction after passing under their lower edges. Intensity reductions equivalent to loudness reductions of 15 to 20 percent have been measured as the direct result of the installation of a single baffle. This reduction takes place when the source and observation point are on opposite sides of the baffle; no reduction is effected on the same side of the baffle as the noise source unless the ceiling is also treated. The effectiveness of multiple baffles in cutting down the transmission of noise will increase as their spacing and height above the floor is decreased and as their vertical area is increased. Baffles are chiefly useful where noise spreading is the principal problem and where partitions cannot be erected for reasons of traffic or ventilation requirements.

It is often desired to cut down the spread of noise from a single machine by means of a more or less complete enclosure such as a booth or cabinet, or possibly by a single part-height partition near the machine. The most effective results take place of course in those directions where an actual barrier is interposed between the source and listener, as on the three closed sides of a booth or on the opposite side of a partition. Transmission from the open side of a booth is not appreciably reduced unless the booth is quite narrow and deep, and the source is as far from the open side as possible. A single partition or shield acoustically treated is totally ineffective when placed on the opposite side of a source from the observer's position; the slight amount of residual reflection from the acoustical surface actually tends to increase the noise transmission rather than re-

duce it. For the same reason, sound absorbent linings in booths do not decrease the level inside the booth below what it would be at the same point of observation without the booth. The interior surfaces of booths should be made as absorbent as possible so that the amplifying effect of reflection from the booth surfaces is made negligible.

In considering the use of acoustical treatment generally, close attention must be paid to the type and distribution of noise sources. As stated before, much more favorable results can be expected of treatment when machines are of differing types, wide spacing, and intermittent operation, than when the opposite characteristics occur. These conditions are usually more important to the success of an acoustical installation than is the average intensity of the noise.

Effects of Sound Conditioning

While the practical benefits of acoustical treatment vary widely in character and degree with the particular type of area and operation, the following have been most frequently reported by industrial personnel:

1. Distraction, annoyance, and general discomfort due to noise are appreciably lowered and a noticeably more comfortable environment is produced. Prolonged ringing in the ears (tinnitus) and partial deafness after exposure to unusually high noise levels are often reported as being markedly reduced or eliminated. Reduction of fatigue and headaches is sometimes mentioned, and there is some evidence that accidents and absenteeism may be decreased.

2. Ease of conversation is almost invariably improved substantially even when reductions in average noise level are comparatively small. Conversation is further facilitated when the sustaining effect of reverberation on intermittent noise impulses is eliminated by treatment, thus making it possible to talk "through" or "between" the noise more easily. The audibility and consequent efficacy of plant loudspeaker systems, for speech, signals, and music, is much enhanced for the same reason.

3. Increased ability to identify and localize individual sound sources is frequently mentioned. This is of particular importance when machine operations are gauged and regulated by ear, or when warnings of danger are given in the form of sound signals.

4. The reduction in the spread of noise is recognized as a "pushing back" of noise toward its source and also as the ability to get out of range of especially intense noise areas more easily. The latter effect is of considerable practical value in situations where workers are not exposed at all times to continuous, intense noise sources at close range, but are normally able to move at intervals into comparatively quiet areas. The more rapid drop-off of noise, due to treatment, is readily apparent and much appreciated.

OTHER QUIETING APPLICATIONS

Restaurants

The problem of quieting noise in restaurants and dining rooms is essentially no different from that of reducing office noise. In a restaurant having a bare floor, plastered walls and ceiling, and no absorption in the form of upholstered chairs or tablecloths, the noise of rattling dishes and silverware and the hum of conversation builds up to a nerve-racking level. This excessive noise not only makes it difficult or impossible for diners to carry on conversations, but also, according to physicians and psychologists, tends to cause a partial paralysis of the digestive organs resulting in nervous indigestion.

It is in this type of restaurant that acoustical treatment effects the greatest relief. In low ceilinged rooms, treatment of the ceiling with a material having a noise reduction coefficient of .60 to .80 will produce generally satisfactory results. For rooms with high ceilings, particularly long narrow rooms of two story height, it is possible to obtain fairly good results by treating the ceiling alone with as highly efficient a material as possible, but it is much preferable to apply a moderately efficient material on both the ceiling and side wall areas.

In the more luxurious type of restaurant or dining room having covered tables, upholstered chairs, and perhaps a carpeted floor and draped windows, we have much the same situation as in the elegantly furnished private office in that there is enough absorption already in the room to produce a partial quieting effect. In such cases it will require much larger quantities of additional absorption in the form of acoustical treatment to effect a substantial reduction of noise level than would be required in a room of the first type containing very little absorption originally.

It frequently happens that although the dining room itself may be satisfactorily quiet, the diners are disturbed by noise which penetrates from the adjoining kitchen. The use of acoustical treatment in the kitchen is of value in reducing this disturbance. In some cases, treating the walls and ceiling of the narrow passageway which often separates the kitchen from the dining room produces surprisingly good results. It must be remembered, how-

ever, that the quieting effect of treatment in either case is limited, and complete elimination of kitchen noise cannot be expected under severe conditions, as when the kitchen connects directly to the dining room by doors which are left open at all times.

Hospitals

There is perhaps no type of building in which quiet is more urgently needed than in a hospital. The effects of noise, which are harmful enough to a healthy person, are greatly aggravated for a hospital patient, and may seriously retard his recovery. Although the truth of this is generally recognized, as evidenced by the posting of "Quiet" signs outside the building, the fact remains that in most cases it is far from quiet inside the hospital itself.

The most serious offender from the standpoint of noise is almost always the corridor. A long, bare, reverberant corridor finished with the typical sound reflective materials acts as a huge speaking tube in that any noise, such as conversation, the slamming of a door, or the cries of patients, created at any point in the corridor is immediately magnified and conducted with undiminished intensity throughout its entire length, and penetrates into every bedroom. As in the case of an untreated office, it is as much the reverberant, pervading quality of the noise as its actual loudness that is responsible for its annoyance to the occupants of the bedrooms.

Noise sources should of course be individually silenced as far as possible by such means as rubber door stops, rubber rims on buckets and utensils, substitution of signal lights for noisy buzzers or bells, and similar measures[5]. However, there will always be a certain amount of uncontrollable noise which will escape into the corridors. For this reason, corridors should always be acoustically treated, even in preference to any other rooms in the building. The effects of treatment are much the same as in a large office, namely a reduction in the intensity of all noises, a considerably greater reduction of distant sources than of those nearby, with a consequent reduction of the "speaking tube" effect, and the elimination of the annoying reverberant quality of all noises.

The decibel reduction analysis does not apply accurately to corridors, owing to their generally irregular proportions, but experience makes it possible to formulate certain working rules. If a corridor is wider than it is high, treatment of the ceiling alone with a material having a noise reduction coefficient of .60 or higher will be satisfactory. For unusually wide and low corridors, a material with a coefficient as low as .50 may be acceptable. If the corridor is narrower than it is high, it is necessary to use as efficient a material as possible if the ceiling alone is treated, but it is preferable to apply less efficient treatment both on the ceiling and on the upper side walls. If a material of .60 or .70 noise reduction coefficient is used, the sum of the width of the ceiling and the heights of the two bands of treatment on the side walls should roughly equal the ceiling height.

In other rooms in the hospital which are apt to be noisy, such as nurseries, delivery rooms, utility rooms, diet kitchens, etc., acoustical treatment is of value in lowering the noise level in the rooms themselves and therefore reducing the noise which may be transmitted to other rooms. In spaces such as laboratories, offices, and dining rooms, treatment is beneficial in providing quiet surroundings for the hospital staff.

Schools

The modern school building, like the hospital and the office building, is finished throughout with highly sound reflective materials, which tend to beset nearly every school activity with the handicap of excessive reverberation and noise. In fact, there is hardly a room in a school building in which acoustical treatment can not be used to real advantage, either for insuring satisfactory hearing conditions or for subduing excessive noise, or, in some cases, for both purposes. The acoustical correction of the auditorium and the music room, and the use of treatment both for acoustical correction and noise quieting in class rooms were fully discussed in the preceding chapter.

As in the case of hospitals, the corridors in the school create a severe noise condition. Sounds escaping into the corridors, as of band or orchestra rehearsals, or the noise of any unusual activity in the corridors themselves, immediately spread throughout the building and cause a disturbance and loss of attention in every class room. Acoustical treatment of all corridors, in accordance with the principles described for hospital corridors, will minimize such disturbances as well as subdue the deafening racket that takes place at every change of class.

The typing class room, unless acoustically treated, becomes a bedlam of noise which makes doubly difficult the task of learning to type. These rooms should be considered as equivalent to exceptionally noisy offices, and treated accordingly.

[5]Charles F. Neergaard, Hospital Consultant in New York City, has done outstanding work along this line.

A crowd of pupils eating and talking in an untreated cafeteria sets up an excessively high noise level. Provision of a more quiet atmosphere by means of acoustical treatment results in lessened nervous tension and excitement, better digestion and nourishment, and improved concentration in the afternoon classes.

The average untreated gymnasium is usually so reverberant that the instructor has difficulty in conducting classes or directing athletics because his voice is not understood. Furthermore, the deafening noise set up during competitive games, especially with spectators present, is confusing and distracting to both the players and the officials. Sufficient acoustical treatment to lower the reverberation time to 2.0 or 2.5 seconds in the empty room generally insures satisfactory hearing conditions together with a substantial noise reduction.

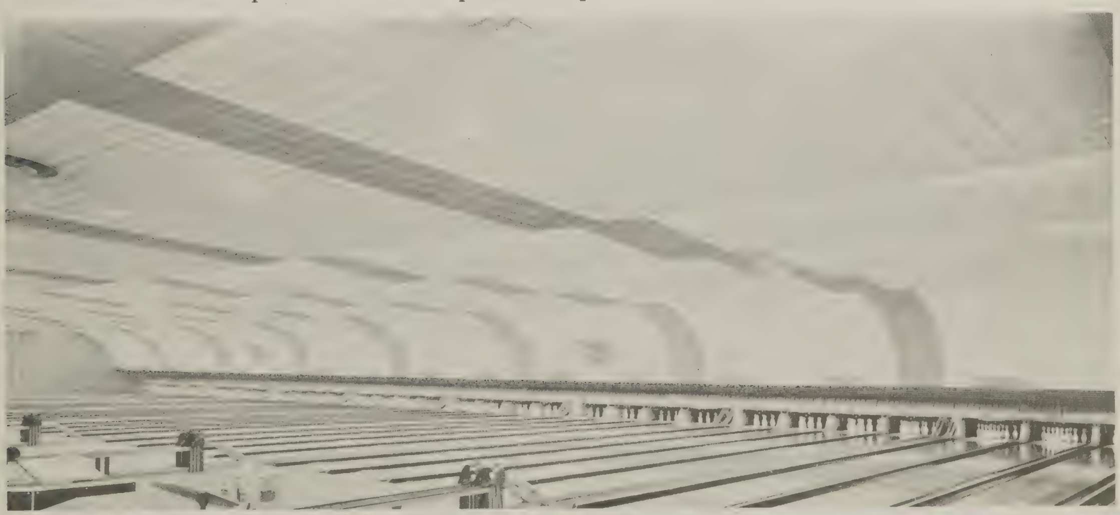
Miscellaneous Noise Problems

Acoustical treatment is successfully used for quieting noise in many other applications aside from those already discussed. Among these are stores, libraries, residences, waiting rooms in railroad stations and airports, club rooms, ball rooms, skating rinks, bowling alleys, rifle ranges, etc. Although the general principles outlined previously are applicable to all of these cases, a few addition comments should be made on some of them.

In quieting bowling alleys it was formerly thought desirable to cut down the pin noise as much as possible, usually by suspending highly absorbent curtain walls in front of the pins and using large amounts of absorption throughout the room. More recent experience has shown that this may be overdone in that excessive muffling of the pin noise may detract from the pleasure of the game for many bowlers. It is now considered best practice to use only enough treatment in the room to eliminate excessive reverberation and to subdue disturbance in the recreational area behind the foul line.

In quieting indoor pistol and rifle ranges, the absorption is largely concentrated around the firing point. Remarkable results in muffling the noise of gunfire and preventing it from spreading to other rooms may be obtained by properly applied acoustical treatment. An article discussing all phases of the design of indoor shooting ranges is available to the interested reader by requesting the pamphlet "Celotex Products in Indoor Pistol and Rifle Ranges," issued by the Acoustical Department of The Celotex Corporation.

Another application of noise quieting with acoustical treatment is found in the increasing use of specially designed sound absorbing materials such as Q-T Ductliner for reducing noise in ventilating and air-conditioning ducts. Complete details covering this phase of noise quieting are given in the pamphlet "Quieting Ventilating Noise with Q-T Ductliner," obtainable on request from the Acoustical Department of The Celotex Corporation.



The Bryn Mawr Recreation Bowling Alley, Chicago, Illinois. Acousti-Celotex tile was applied to ceiling and rear wall.

A sound-absorbing ceiling of Acousti-Celotex tile creates a quiet, dignified atmosphere in the Bank of America, Los Angeles, California. Architect, Raymond L. Shaw.

Chapter VII

Sound Insulation

A COMMON ACOUSTICAL PROBLEM in building construction is the transmission of sound through walls, floors, and ceilings. In practically all types of construction, transmission of sound from one room to another through the dividing wall or floor takes place as a result of diaphragmatic vibration. The surface may be set into vibration either by direct mechanical impact, as by a footstep on a floor, or by the alternating air pressure due to sound waves incident on the surface. The former case is referred to as *impact transmission* and the latter is termed *airborne transmission.* In either case the vibrating surface generates new sound waves of reduced intensity in the room on the other side.

Rating of Efficiency—Transmission Loss

The sound insulating efficiency for airborne sound of a wall or floor construction is called its *transmission loss* (T.L.) and is measured in decibels. The transmission loss is simply the number of decibels which a sound loses in being transmitted through a wall. For example, if a sound of 70 db. intensity level passes through a partition having a transmission loss of 30 db., it will have an intensity level of 70 less 30, or 40 db. on the other side. (See Fig. 7.1.) The transmission loss of any wall is a physical property of that wall, just as is its weight or rigidity, and depends only on the materials and method of construction used in erecting the wall, and not on the loudness of the sound striking it nor on the size or acoustical properties of the rooms on either side of it.

The transmission loss of a given wall does, however, vary considerably with the frequency of the sound. In general, partitions and floors are much more efficient for high frequency sounds than for low frequency sounds. Constructions are therefore tested at a number of frequencies covering the entire scale, and the figure given for the transmission loss is the average of the values thus obtained. This varying efficiency with frequency ex-

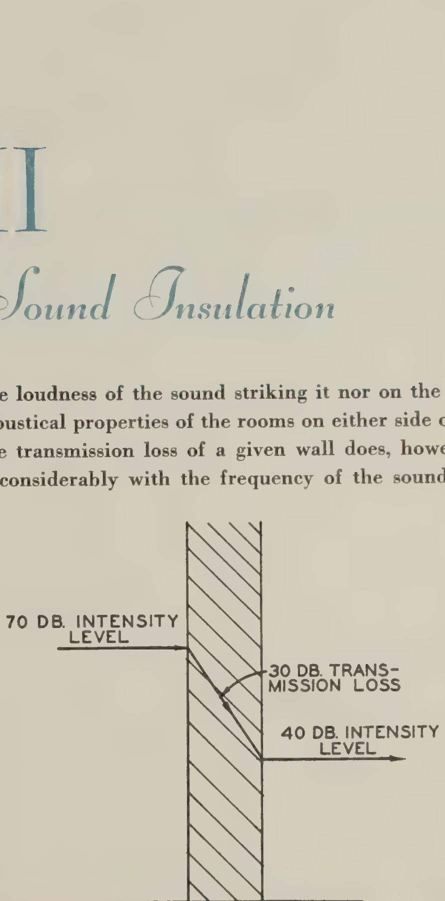


FIG. 7.1—*Reduction in intensity level of sound passing through a wall having a 30 db. transmission loss.*

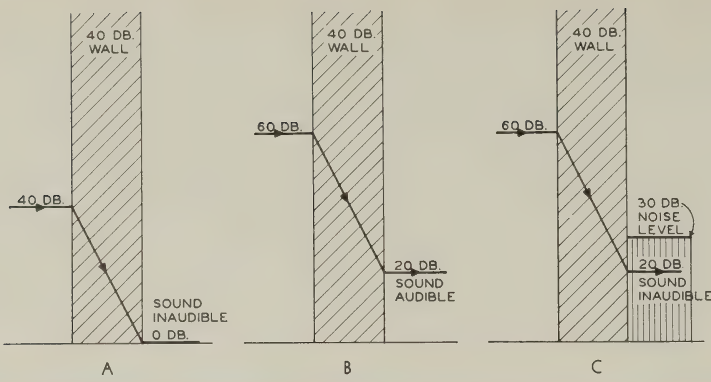


FIG. 7.2—*Effect of original loudness of sound and level of extraneous noise on the "listening" side in determining audibility of sound through a wall having a given transmission loss.*

plains why conversation sometimes is heard through a wall as a low pitched rumble of sound, but cannot be understood. The higher pitched overtones of the speech sound, on which intelligibility depends, are not transmitted as readily as the low pitches.

Original Loudness of Sound

The loudness of the sound heard through a partition depends of course on the loudness of the sound striking it on the other side. Fig. 7.2 shows the performance under various conditions of a wall having a transmission loss of 40 db. In Fig. 7.2-a, the sound striking the wall has an intensity level of 40 db., it undergoes a reduction of 40 db. in passing through the wall, and emerges on the other side at an intensity level of 0 db., which is inaudible. If, however, the original sound is 60 db., as in Fig. 7.2-b, the 40 db. wall will reduce it to 20 db. on the other side, where it can be heard faintly. Thus the wall would be "sound-proof" provided the sound striking it was not over 40 db., but it would not be sound-proof against sounds louder than 40 db., and a wall having a higher transmission loss would be required to give satisfactory results.

Effect of Noise

In the above example it was assumed that we were listening to sound coming through a wall into a room which was otherwise absolutely quiet. In reality, there are very few places in which there is not at least a slight amount of noise, such as the ticking of a clock, the rumble of distant street traffic, and sounds from many different sources. The human ear behaves in such a way that it cannot hear a faint sound when a loud sound is present at the same time. No one can hear a whisper in a boiler factory, because it is drowned out or "masked" by the surrounding noise. In the case of sound coming through a wall we can hear it only if the room is quiet enough. Usually we do not hear the neighbor's radio through the wall when our own radio is turned on, in which case the wall is "sound-proof." But if we turn off our radio and are trying to go to sleep, the wall is no longer "sound-proof," and the neighbors' radio is heard all too plainly. This is illustrated in Fig. 7.2-c. A 60 db. sound is reduced to 20 db. by the wall, exactly the same as in Fig. 7.2-b, but the noise level of 30 db. drowns out the sound coming through the wall and it cannot be heard. (Experiments on hearing have shown that one sound must be at least 10 db. louder than a second sound in order to drown it out.) In Fig. 7.2-b, there is no interfering noise, and the sound can be heard through the wall.

Estimating Sound Insulating Requirements

The foregoing shows that a given wall construction may or may not give satisfactory sound insulating performance, depending on the conditions in individual cases, and that in order to determine the efficiency that a wall must have in order to be satisfactory one must know approximately both the loudness of the sound which will strike one side, and the loudness of the interfering noise which will be present on the other side.

Transmission Loss of Wall	Hearing Conditions	Rating
30 db. or less	Normal speech can be understood quite easily and distinctly through the wall.	Poor
30 to 35 db.	Loud speech can be understood fairly well. Normal speech can be heard but not easily understood.	Fair
35 to 40 db.	Loud speech can be heard, but is not easily intelligible. Normal speech can be heard only faintly, if at all.	Good
40 to 45 db.	Loud speech can be faintly heard but not understood. Normal speech is inaudible.	Very good — recommended for dividing walls between apartments.
45 db. or greater	Very loud sounds, such as loud singing, brass musical instruments, or a radio at full volume can be heard only faintly or not at all.	Excellent — recommended for band rooms, music practice rooms, radio and sound studios.

FIG. 7.3—*Classification of sound insulating properties of partitions according to their average transmission loss. A noise level of approximately 30 db. is assumed on the listening side in each case.*

As an approximate working rule, the following may be given:

Subtract the level of the interfering noise on one side of the partition from the level of the sound which strikes the other side, and add 10 decibels. The result is the transmission loss which the wall must have in order to be reasonably satisfactory.

This rule is not rigid, and in case of doubt it is advisable to provide a wall 5 or 10 db. better than the rule indicates. The data in Fig. 1.3 furnishes a rough guide to the levels of commonly encountered sounds. Actual experience, however, is of the most value in estimating sound insulating requirements. Observations on the transmission of speech through walls of known efficiency have shown the results given in Fig. 7.3, quiet conditions (about 30 db.) on the "listening side" being assumed in each case.

Effect of Openings in Partitions

The published values of transmission loss for partitions and floors are based on tests made on constructions having no openings of any kind. If a door or window having a low transmission loss is placed in a wall of high efficiency, the overall transmission loss of the combination will be intermediate between the two values, depending on the area of the door or window in relation to that of the wall, and on the difference in efficiency between the two. This is illustrated in Fig. 7.4.

The effect of cracks or holes, such as those occurring around doors, pipes, phone or outlet boxes, etc., is especially serious, as they may greatly reduce the efficiency of an otherwise satisfactory wall construction.

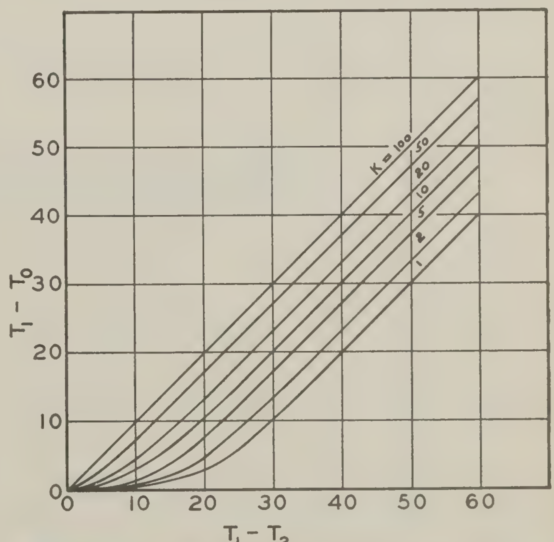


FIG. 7.4—*A door or window having a transmission loss of T_2 decibels, occupying K percent of the total area of a wall having a higher transmission loss of T_1 decibels, will reduce the effective transmission loss of the wall by (T_1 — T_0) decibels.*

Sound Insulating Properties of Partitions

Tests on the sound insulating properties of partitions have established the following facts:

1. For solid masonry partitions such as brick, concrete, or tile, the transmission loss depends only on the weight of the wall per unit area. The heavier the wall the better the sound insulation. As an approximate rule, starting with a solid masonry partition weighing 10 lbs. per sq. ft. and having a transmission loss of 26 db., each successive doubling of the weight adds 9 db. to the transmission loss.

2. An exception to the above weight law is found in the case of porous concrete masonry. The efficiency of such walls is consistently higher than that of ordinary masonry walls of the same weight. For example, an ordinary masonry wall weighing 30 lbs. per sq. ft. would have a transmission loss of 40 db. according to the weight law, but a wall built of Celocrete* lightweight concrete blocks 4 inches thick, plastered both sides, having the above weight has a value of 44 db. It is important to note, however, that porous concrete partitions show this superiority *only when they are plastered on at least one side and preferably on both sides.* If plaster is omitted, sound waves pass readily through the pores of the material, with the result that the sound insulation is generally unsatisfactory.

3. A masonry partition having the plaster base and plaster furred out on both sides is considerably better than a partition of the same weight with plaster applied direct.

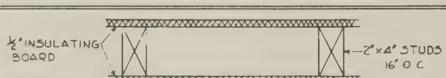
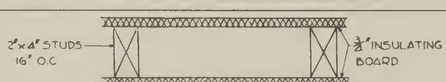
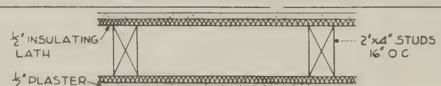
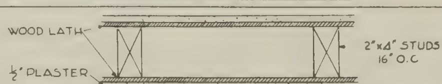
*Reg. U. S. Pat. Off.

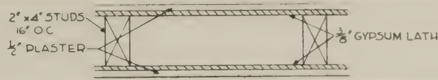
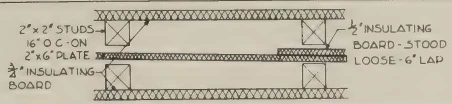
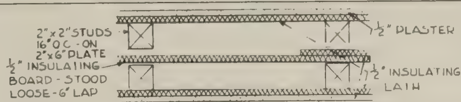
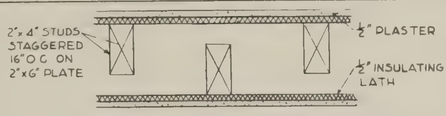
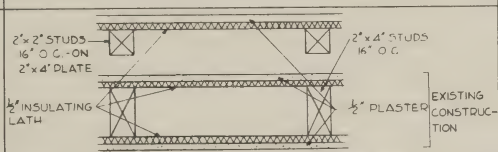
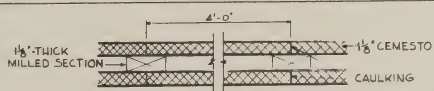
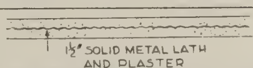
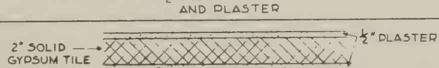
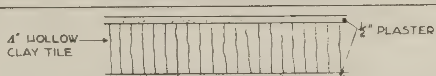
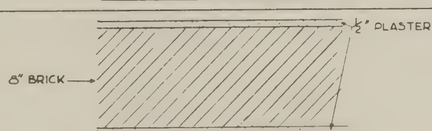
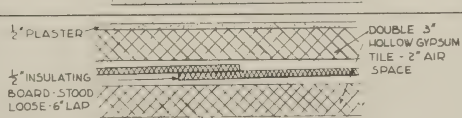
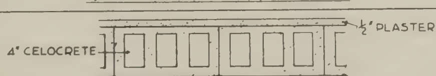
4. The efficiency of single wood or steel stud walls cannot be accurately predicted, but in every case is greater than that of an equal weight of solid masonry. The efficiency may be increased by making the connection between the plaster base and the studding as flexible as possible. Placing a rock wool blanket between the studs and the plaster base, spacing the blanket from the plaster base by means of furring strips, also raises the efficiency considerably.

5. For double walls, the sound insulating value depends on the weight and rigidity of the two units, and particularly on the degree of structural separation. The fewer the points at which the units are rigidly tied together, the better the sound insulation. For best results, double walls should be connected only at the edges. Even a small connection, such as a single nail driven through both sides of a double wall, reduces its efficiency by conducting vibration directly across the air space. The efficiency may be increased somewhat by inserting pads of Celotex Building Board at the top and bottom edges so as to further decrease the transmission of vibration at these points.

6. Wall fills, such as slag, loose rock wool, etc., should never be used in a structurally separated double wall, since they act as a bridge across the air space and thus reduce the sound insulation value. Porous materials in the air space are of some value, however, when they are placed so as not to create bridging action. For example, a rock wool blanket may be attached to the inner faces of staggered wood studs, or may be adhered to one inner

TABLE I. Sound Transmission Tests on Partitions. All Tests Except those Marked (*) Were Sponsored by the Insulation Board Institute.

Test No.	Construction	Weight, Lbs. per Sq. Ft.	Transmission Loss, Db.	Class
1.		3.8	32.2	Fair
2.		4.3	32.7	Fair
3.		12.6	40.9	Very Good
4.		17.1	37.5	Good

Test No.	Construction	Weight, Lbs. per Sq. Ft.	Transmission Loss, Db.	Class
5.		15.0	34.9	Fair to Good
6.		6.2	42.8	Very Good
7.		14.3	52.3	Excellent
8.*	 †This value was obtained some years ago by a method now obsolete, and is not strictly comparable to other values in this table. The figure shown is probably somewhat high.	13.1	53.7†	Excellent
9.		18.2	51.3	Excellent
10.*		8.2	39.8	Good to Very Good
11.*		13.9	29.6	Poor
12.*		19.6	34.2	Fair
13.*		27.0	39.8	Good
14.*		88.0	53.8	Excellent
15.*		32.0	47.8	Excellent
16.*		30.0	43.8	Very Good

face of a double masonry wall without touching the other side. Sheets of Celotex Building Board stood loosely in the air space provide increased sound insulation.

For hollow walls which are not structurally separated, such as ordinary wood stud partitions, a fill between the studs improves the efficiency slightly by increasing the weight per unit area.

7. Results comparable to those obtained with completely separated double walls can also be achieved by attaching furred plaster construction to a structural wall by means of special resilient members, employing felt pads or steel springs. These units hold the furred construction in place, and reduce the intensity of vibration conducted to the structural wall.

Sound Transmission Test Data on Partitions

Listed in Table I are the results of tests of the sound insulating efficiencies of various partitions embodying both standard and special constructions. Each figure shown is the average of measurements made at a series of frequencies covering the audible range. These tests were made at nationally recognized laboratories,[1] and except where otherwise noted were conducted under the sponsorship of the Insulation Board Institute.

Tests 1 to 5 indicate that high sound insulating value cannot be obtained on standard wood stud constructions if they are left unplastered. Application of plaster to both sides effects considerable improvement, due to the large increase in weight. Of the plastered walls in this group, Celotex Lath as a plaster base is seen to be superior in sound insulation to either wood lath or gypsum lath.

The double 2x2″ stud partitions (Tests 6 and 7) have remarkably high sound insulating efficiency in relation to their weight, thickness, and cost, and are comparaitvely easy to erect. The two sides of the wall are structurally separated at all points except the floor and ceiling, where the studs are nailed to 2x6″ plates. Note again that the plastered wall is considerably better than the unplastered one. This construction is recommended only for *non-load bearing partitions of normal height.*

The staggered stud construction (Test 8) is recommended as a load bearing double wall having high sound insulation. Frequently a rock wool blanket is woven between the studs for obtaining somewhat higher efficiency.

Test 9 shows the effect of improving an existing wall of standard 2x4″ stud construction by erecting an auxiliary 2x2″ stud partition on one side of it. Comparison with Test 3 shows that the added construction increases the efficiency by about 10 db., which is a decidedly worthwhile improvement. As in the case of the 2x2″ double stud wall (Tests 6 and 7), structural separation should be maintained at all points except the floor and ceiling. Further improvement can be obtained by standing loose sheets of Celotex Building Board in the air space, and also by erecting a second auxiliary partition either on the same side or on the oposite side of the existing wall.

The Cemesto* party wall shown in Test 10 has been developed in connection with low cost housing embodying dry wall construction. It is comparable in efficiency with a standard 2x4″ stud partition with Celotex Lath and plaster on both sides, and has high enough sound insulating value to make it suitable as a dividing wall between apartments. All joints must be caulked to prevent sound leakage.

Tests 11 to 14 on solid masonry partitions are listed for comparison with wood stud constructions and to illustrate the effect of weight in determining the sound insulating efficiency of solid masonry as previously described. It is seen that high sound insulation is obtained only by the use of excessive weight as compared with double constructions, such as that shown in Test 15.

The double 3″ gypsum tile partition with loose sheets of Celotex Building Board stood in the air space (Test15) provides excellent sound insulation in masonry construction comparable to the 2x2″ double stud or the 2x4″ staggered stud partitions. As in all double walls, structural separation must be maintained throughout. It is important that care be exercised in laying the tile so that none of the mortar is squeezed out into contact with the Celotex Building Board so as to bind the Building Board between the two sections.

The 4″ Celocrete* partition shown in Test 16 illustrates the superiority of lighweight concrete masonry to ordinary masonry of the same weight, as previously referred to. According to the weight law, a solid masonry wall weighing 30 lbs. per sq. ft. would have a transmission loss of about 40 db, as compared with 43.8 db for the Celocrete wall. In common with all porous concrete constructions, *the Celocrete wall must be plastered on at least one side,*

[1]*Sound Insulation Values of Floors and Walls,* issued by Insulation Board Institute, 111 W. Washington St., Chicago 2, Ill. See also National Bureau of Standards Report BMS 17, and Supplement, *Sound Insulation of Wall and Floor Construction,* by V. L. Chrisler, obtainable from the Superintendent of Documents, Washington, D. C., price 15c. Additional data is given in the texts listed at the end of this book.

*Reg. U. S. Pat. Off.

and preferably on both sides, in order for its sound insulating value to be realized.

Sound Insulating Properties of Floors

Transmission of sound through floors may be either of the airborne or impact type. Fireproof floor constructions such as concrete or tile are very efficient against airborne sound, due to their necessary weight and rigidity. Transmission losses of 45 to 60 db. are typical. Impacts, however, when made on a bare concrete floor surface, are transmitted very readily. The best method of reducing impact transmission is to cover the floor with a soft resilient material, such as heavy carpet or cork tile, which acts to muffle and absorb the shock of the impact.

The addition of a suspended lath and plaster ceiling below the tile or concrete slab provides high insulation against both impact and airborne sound. Still better results can be obtained by suspending the ceiling from resilient hangers which tend to absorb rather than conduct vibration.

Additional insulation against both airborne and impact sound may also be obtained by installing a "floating" floor over the structural floor. The floating floor may be a separate concrete slab separated from the main slab by spring isolators, or it may be a wood floor nailed to sleepers which are supported either by steel springs or by sheets of resilient material such as Celotex Building Board. In any case, the efficiency of such construction depends both on the weight of the floating floor and on the degree of vibration isolation achieved by the resilient mountings.

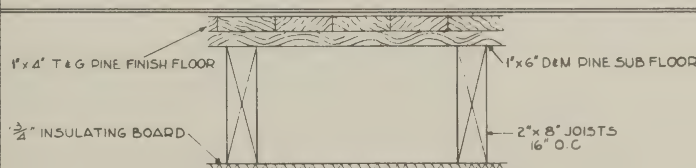
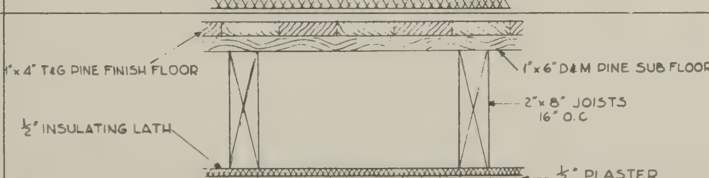
Ordinary wood joist floor constructions, with lath and plaster on the under side of the joists and rough and finish flooring on top, have efficiencies for airborne sound averaging around 40 to 45 db, which are somewhat higher than standard wood stud partitions. Higher insulating value may be obtained by using a floating floor or separate ceiling joists, or preferably both.

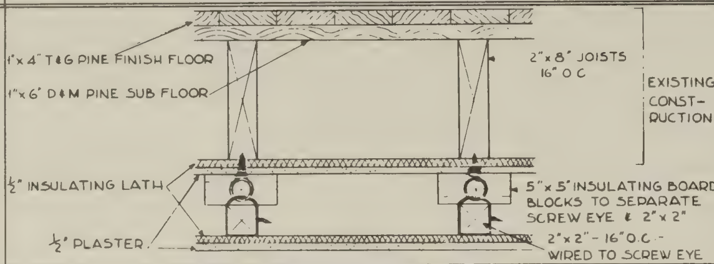
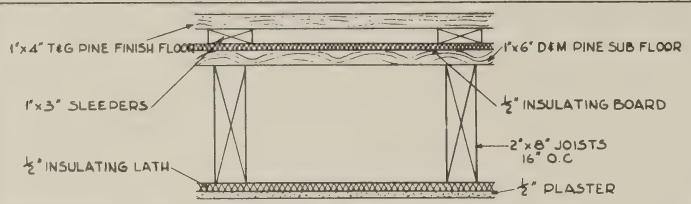
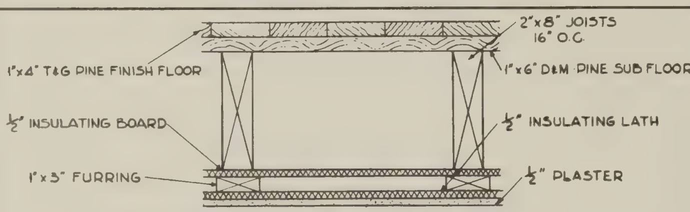
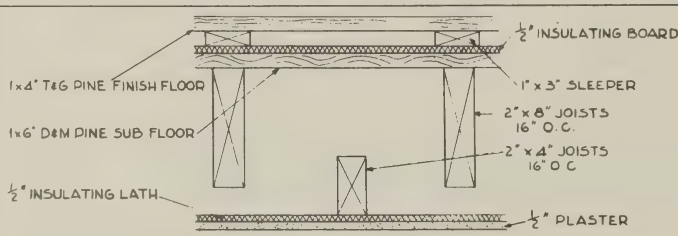
The insulation of impact transmission in wood joist construction is a much more difficult problem, and under severe conditions such as running and jumping or the vibration and impact of heavy machinery on the floor above it is virtually impossible to secure completely satisfactory results. Light impacts such as ordinary footsteps, which are not heavy enough to shake the whole floor, can be muffled satisfactorily by means of heavy carpet or resilient floor material or by installation of a floating floor. These measures are not effective against heavy impacts, because the usual frame construction is not massive and rigid enough to resist being set into vibration as a whole. The only construction which will do any good at all under heavy impacts is the erection of a completely separated ceiling with joists anchored only in the side walls. Even this may be inadequate when the walls are of ordinary frame construction,since vibration may be transmitted through the wall connections. If the walls are of heavy masonry, however, better results may be expected.

Sound Transmission Test Data on Floors

The wood joist floor constructions shown in Table II

TABLE II. Transmission Tests for Airborne Sound on Floor Construction Sponsored by the Insulation Board Institute.

Test No.	Construction	Weight, Lbs. per Sq. Ft.	Transmission Loss, Db.
1.		9.6	40.2
2.		14.3	45.1

Test No.	Construction	Weight, Lbs. per Sq. Ft.	Transmission Loss, Db.
3.		20.3	55.5
4.		16.2	49.7
5.		15.9	47.4
6.		16.7	54.1

were tested under the auspices of the Insulation Board Institute.

Comparison of Tests 1 and 2, on standard 2x8″ wood joist floors, shows that elimination of a plaster finish on the ceiling reduces the efficiency by about 5 db. The value shown for Test 2 is typical of standard floor construction using Celotex Lath as a plaster base.

In Test 3,an auxiliary ceiling of insulating lath and plaster on 2x2″ joists has been suspended from the existing construction of Test 2, resulting in an improvement in sound insulation of about 10 db. and providing efficiency equivalent to heavy masonry construction. In this construction, transmission of vibration between the existing and auxiliary ceilings is minimized by the blocks of insulating board which prevent the 2x2″ members from being pulled into rigid contact with the screw eyes.

Tests 4 and 5 are variations of standard floor construction which are applicable to new work. In Test 4, illustrating "floating" construction, the finish flooring is nailed to wood sleepers which are separated from the sub-flooring by a sheet of Celotex Building Board. The high efficiency of this construction depends on the sleepers being nailed only into the Building Board and not through the Building Board into the sub-flooring. An alternative method is

to nail the sleepers through into the sub-flooring but only at intervals of 6 to 8 feet.

A combination of a floating floor and a completely separate ceiling, as shown in Test 6, results in extremely high sound insulating efficiency. The ceiling joists are not connected to the floor joists at any point but are supported only at the side walls or at the intermediate points at which the floor joists are supported. This construction represents about the maximum efficiency obtainable in frame buildings within reasonable limits of thickness and cost. The vibration isolating action of the separate ceiling makes it particularly effective against heavy impacts, up to the point where the entire building structure is set into vibration.

Doors

Obviously the overall sound insulating efficiency of a partition is limited by the characteristics of the doors within the partition. This efficiency can be increased by sealing any cracks or openings which may exist, as by providing felt or rubber gaskets on the door stops at the head and jambs, and installing a special metal bound felt strip threshold closer. See Figs. 7.5 and 7.6.

A heavy flush door is more efficient than a light panel door, but generally speaking, ordinary door construction

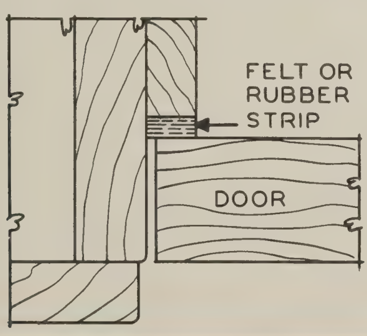


FIG. 7.5—*Detail of door jamb showing method of sealing crack against sound leakage.*

does not have a sound reduction of more than 25 db. If more reduction is necessary, either double door construction with a small vestibule is necessary, or one of the special sound insulating doors specifically manufactured for that purpose.

[2]Taken from the complete list of published Riverbank Laboratories Sound Transmission data in *Acoustics and Architects* by P. E. Sabine, McGraw-Hill Book Co., Inc., New York.

Given in Table III are test values obtained at Riverbank Laboratories.[2] All the units were sealed tightly into place except No. 5, which was mounted loosely as in actual practice.

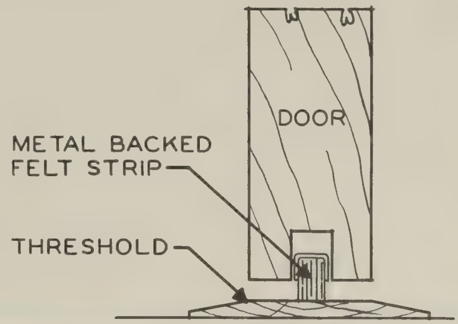


FIG. 7.6 — *Automatic threshold closer for sealing bottom crack of door. Felt strip raises into door when door is opened.*

TABLE III. Riverbank Laboratories Tests on Sound Transmission of Doors.

	Transmission Loss, Db.
1. Steel, ¼″ thick	35
2. Wood refrigerator door, 5½″ thick, filled with cork	29
3. Solid oak, 1¾″ thick	25
4. Fabricated, hollow flush or sanitary door, 1¾″ thick	27
5. No. 4, hung in the usual manner	24
6. Light 4-panel birch veneer	22
7. Two doors, panelled maple veneer, hung with 2″ separation in single casement	30
8. Special soundproof door, 1¾″ thick	35
9. Special soundproof door, 2½″ thick	40
10. Special soundproof door, 3″ thick	43

Windows

High sound insulation in windows is seldom required except for observation windows in radio and recording studios. These should be constructed with double or triple panes of heavy glass, with each pane isolated completely from the frame by gaskets of felt or rubber around all four edges. It is advisable to have the panes of slightly different thickness, to avoid resonance effects. When a double window is placed in a double wall, the structural separation should be maintained at the window by constructing separate rough bucks and frames in each side of the double wall. (See Fig. 7.7).

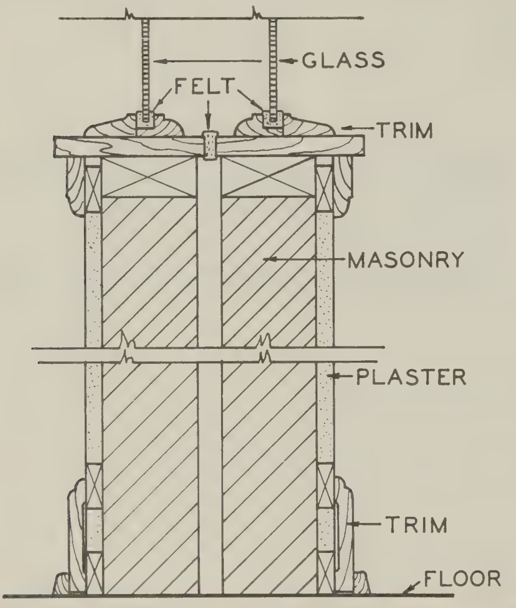


FIG. 7.7—*Detail of sound insulating window construction, showing complete structural separation of double wall.*

Improving Existing Construction

The best method of increasing the sound insulation of an existing partition is to erect an auxiliary partition which is spaced an inch or two away and does not touch the existing partition at any point. The auxiliary partition may be built of masonry, with a coat of plaster on the outside, or may be constructed of 2 x 2" studs, as shown in Fig. 7.8. Increases of 10 to 15 db may generally be expected

For reducing transmission through floors, either the floating floor construction shown in Tests 4 and 6 of Table II may be built over the existing floor or the auxiliary ceiling construction shown in Fig. 7.9 may be used. In this construction the joists supporting the auxiliary ceiling are supported only at the walls, and do not come in contact with the existing ceiling at any point. In the case of severe impact conditions on existing frame construction, it should not be attempted to secure satisfactory improvement by installing the floating floor construction. The independent auxiliary ceiling should be erected instead, it being remembered that in general only a moderate improvement can be expected.

Where space does not permit the installation of the auxiliary ceiling supported only at the walls, the directly suspended auxiliary construction shown in Test 3 of Table II will provide nearly as good results for airborne sound. As indicated, an improvement of about 10 db can be achieved. Under conditions of heavy impact, however, the results of this auxiliary construction are liable to be disappointing.

Acoustical Treatment

The question is frequently asked whether the sound transmission between two rooms can be increased satis-

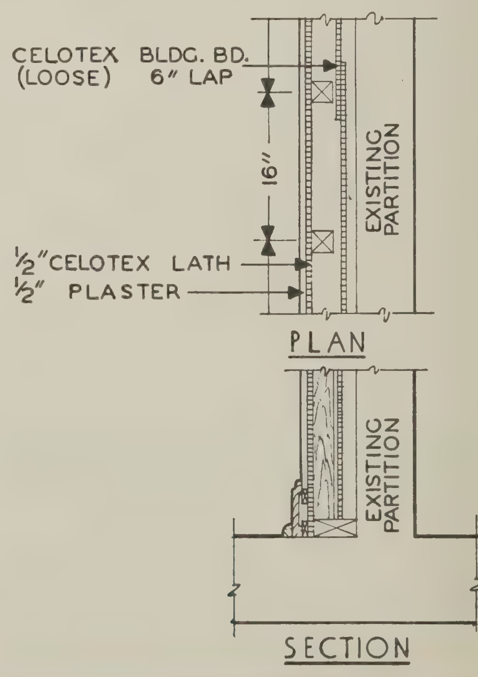


FIG. 7.8—*Construction of 2x2" stud auxiliary partition.*

factorily by the use of acoustical treatment in one or both rooms. The answer is in general "No." Covering the surface of a ceiling or wall with acoustical material adds inappreciably to its transmission loss. An acoustical treatment properly applied will produce a satisfactory quieting effect in the room in which it is installed, and will naturally reduce the amount of sound to be transmitted, thus increasing indirectly the apparent sound insulating efficiency of the wall. However, experience has shown that a considerably greater reduction in the transmitted sound is usually necessary for satisfactory results than is possible to obtain by acoustical treatment.

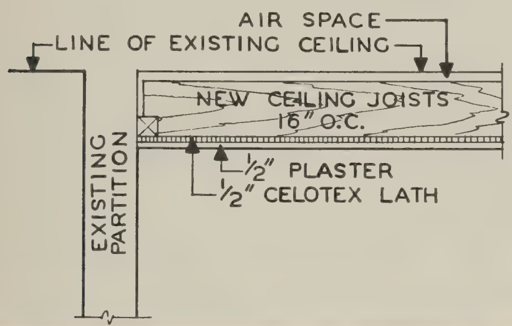


FIG. 7.9—*Construction of auxiliary ceiling with joists suspended only at ends.*

Machine Isolation

Another type of problem which frequently occurs is the transmission of machine vibration through a building structure. As in the case of impact transmission discussed above, the floor on which the machine is fastened is directly set into vibration which in turn generates sound waves in the room below. In buildings of modern fireproof construction it is quite possible for this vibration to be conducted readily along the continuous steel framework and to appear as audible sound in rooms far removed from the machine causing the vibration. Occasionally vibration may be of so low a frequency as to be inaudible, but will be violent enough to cause rattling of light fixtures, metal cabinets, etc.

In the majority of cases the simplest and least expensive method of reducing the transmission of machine vibration is to provide a resilient mounting for the machine which will tend to cushion and absorb the vibration rather than to transmit it directly to the building structure. Although space does not permit a complete discussion of this subject, the essential points to be observed in designing resilient mountings may be summarized as follows:

1. If a machine which is not operating is placed on a spring (or a number of springs) and is pushed down and suddenly released, it will bounce up and down at its *natural frequency*. The heavier the machine and the softer the springs, the lower will be the natural frequency. When the machine is started in operation, the spring mounting will be subjected to a vibratory force of an intensity dependent on the degree of unbalance of the moving parts, and having a *driving frequency* determined by the speed of operation of the machine.

2. The lower the natural frequency of the machine on its spring mounting in comparison to the driving frequency, the more efficient will be the mounting in absorbing the vibration. The natural frequency should be not greater than 1/5 of the driving frequency, and preferably not over 1/10th, although as the natural frequency is lowered beyond 1/10 of the driving frequency, no appreciable improvement is gained.

3. In order for a resilient mounting to absorb vibration effectively the loading placed on it must not exceed the point below which the deflection is directly proportional to the load. For example, a steel coil spring loaded so heavily that it "hit bottom" would obviously have no vibration isolating value. At the same time, the resilient unit should be loaded as heavily as possible without exceeding this limit in order for the natural frequency to be brought as low as possible. It follows, then, that the most effective vibration isolator is the one which is the softest and still has the highest load limit. To quote a homely example: a truck spring would not work on a baby carriage, because although the load limit is high enough the spring is too stiff, and the reverse case would be equally unsatisfactory because although the spring is soft enough it could not handle the load.

4. The placing of a resilient mounting under a machine in such a manner as to minimize the transmission of vibration generally results in increased vibration of the machine itself, since it is more free to move than when it is bolted rigidly to the floor. When this vibration is objectionable, it may be reduced by increasing the weight of the machine. This is most easily done by making a separate concrete base to which the machine is rigidly fastened, and then mounting the machine and base together on resilient supports. With the added weight the resilient mountings will have to be stiffer than before in order to carry the new load.

The materials most commonly used for resilient machine mountings are cork, rubber, and steel coil springs. The latter can be designed to have almost any stiffness and load limit, especially when used as suspension rather than compression members, and are therefore capable of providing very effective vibration isolation under a wide variety of conditions. Due to their low damping properties, however, they tend to cause more vibration of the mounted machine than cork, rubber, or similar organic materials.

Pads of cork, rubber, fibre board such as Celotex Building Board and other compliant materials can also be used successfully under most conditions. Pads placed under a machine should have a total load bearing area such that the loading per square inch is just under the load limit of the particular material used. Increasing the thickness of the pad gives improved isolating efficiency, but does not change the load limit of the material.

Several of the leading tire and rubber manufacturers have designed isolating units employing rubber bonded to steel anchoring members. These are convenient and practical to use, and give satisfactory results when used under the conditions for which they are designed. The manufacturers also furnish technical data and recommendations for the use of these units.

READING LIST

The following list of books on architectural acoustics is recommended to those who wish to study the subject in further detail. Some of these books constitute the original sources from which much of the material in this volume has been drawn.

Knudsen and Harris, *Acoustical Designing in Architecture*. John Wiley & Sons, Inc.

A detailed and comprehensive treatise on all phases of the subject.

Olson, Harry F., *Elements of Acoustical Engineering* (2nd edition), D. Van Nostrand Company, Inc.

An up-to-date work emphasizing recent developments in electro-acoustics.

Rettinger, Michael, *Applied Architectural Acoustics*, Chemical Publishing Company, Inc.

This book covers studios, sound stages, etc., in considerable detail.

Sabine, Paul E., *Acoustics and Architecture*, McGraw-Hill Book Co., Inc.

A concise treatment of both the theoretical and practical aspects of architectural acoustics.

Sabine, Wallace C., *Collected Papers on Acoustics*, Harvard University Press (out of print).

These papers, reporting the original experimental work of Professor Sabine, form the foundation of modern architectural acoustics.

Watson, F. R., *Acoustics of Buildings* (3rd edition), John Wiley & Sons, Inc.

The practical fundamentals of the subject presented in a form especially suited to the non-technical reader.

Watson, F. R., *Sound*, John Wiley & Sons, Inc.

An elementary text on the physics of sound.

Morse, Philip M., and Bolt, Richard H., *Sound Waves in Rooms*, Reviews of Modern Physics, Vol. 16, No. 2, April, 1944, American Institute of Physics.

A detailed review of the newer mathematical theory of room acoustics, based on analysis of the normal modes of vibration of the air in a room and their relation to the acoustical impedance of the room surfaces.

In addition to these books, the reader may find of interest the issues of the Journal of the Acoustical Society of America, in which current developments in all branches of acoustics are reported. For further information address Wallace Waterfall, Secretary, Acoustical Society of America, 57 E. 55th Street, New York 22, N. Y.

Those interested in the use of acoustical materials are also invited to address the Acoustical Materials Association, 57 E. 55th Street, New York 22, N. Y., requesting the Official Bulletin of the Association. This bulletin, published periodically, contains absorption coefficients and other data on current acoustical products of all Association members.

Information on currently adopted or proposed Standards on acoustical terminology, practices, measurements, etc., may be obtained from American Standards Association, 70 East 45th Street, New York 17, N. Y.

APPENDIX

Absorption data and specifications on all Celotex Acoustical Products are published annually in the Acoustical Materials Association Bulletin and in Sweet's Catalog. For current information, these sources should be consulted.

Celotex Acoustical Products

More than 25 years ago the first Celotex acoustical material, Acousti-Celotex Cane Tile, was placed on the market. This product was a tile cut from Celotex cane fibre board, which was then face-perforated with 400 one-quarter inch diameter holes per square foot. In spite of its crude appearance, the advantages of an acoustical treatment in rigid tile form having high sound absorbing efficiency, complete and permanent paintability, light weight, and ease of handling and application, won for it an immediate acceptance.

Since that time the product has been constantly improved in appearance and efficiency and reduced in price. The basic idea of a perforated paintable tile has remained unchanged, however, with the result that today Acousti-Celotex Cane Tile leads all other acoustical tiles in footage installed.

In the meantime, the use of sound conditioning expanded so widely that no single acoustical material could be expected to satisfy all demands. The line of Celotex Acoustical Products has, therefore, been extended to now include sound absorbing products of different materials and distributed under the trade marks Acousti-Celotex Cane and Mineral Tile, Fissuretone, Acousteel, Q-T Ductliner and Q-T Studio Element. Also available are perforated asbestos and hardboards which are used as facing for various types of sound absorbing elements.

Table I lists the sound absorption coefficients of all Celotex Acoustical Products as determined by the official laboratory of the Acoustical Materials Association.

Table II lists the coefficients of common building materials and of auditorium seats and audiences, as given in the Bulletin of the Acoustical Materials Association. More complete listings will be found in the textbooks on architectural acoustics.

Erection of Celotex Acoustical Products

A quarter century of experience in manufacture, research and field application has provided Celotex with a storehouse of valuable information about the erection of acoustical tiles. Celotex Acoustical Products can be installed in a number of different ways as individual circumstances may dictate. The following are the most commonly used methods.

The adhesive method has a number of advantages. By varying the thickness of the adhesive pads, a moderate amount of unevenness in plaster or concrete surfaces can be compensated for. It is a quiet method of installation, which is an important factor in occupied spaces, particularly in hospitals. This method of installation permits application of the tiles in any variety of pattern

arrangements with little difference in application costs. Adhesives used are of the heavy-bodied type. Distributors of Celotex Acoustical Products know the type and quantity of adhesive that should be used with the different products under differing conditions, the proper technique of placing the tile in position, and how to prepare the surface to receive the tile.

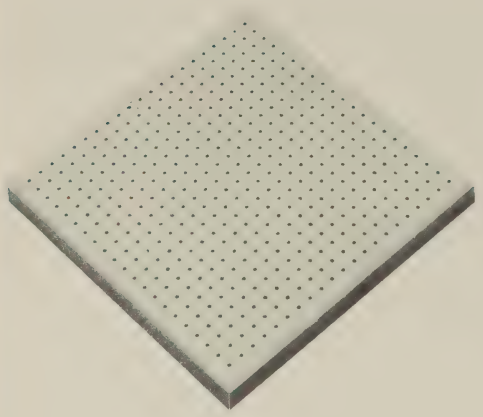
The next most common method is to attach the acoustical tiles to wood furring strips or wood decking by means of nails or screws. This method is used most widely with mechanically perforated tiles where the nail or screw heads can be concealed in the perforations. Where erection is against wood furring strips, it is good practice to apply a course of building paper immediately behind the acoustical tiles to prevent discoloration from breathing through joints. Proper spacing of furring strips is important. The allowable maximum is determined by the unit size of the tiles and the physical characteristics of the product. Sagging or cupping of tiles may result from placing furring strips on insufficiently close centers.

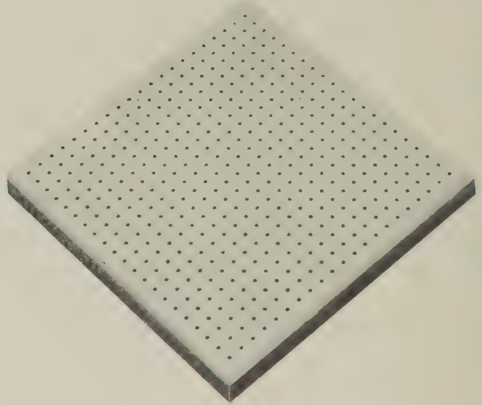
Acousti* Lock Board in conjunction with metal furring strips is an ingenious suspended ceiling construction that is gaining widespread approval and use. Acousti Lock Board is a special screw-holding gypsum board assembly. Its screw-holding power is provided by means of an extra membrane selected for that purpose, laminated into the assembly. The long edges of the finished board are ship-lapped and end joints are closed with tightly fitting clips, or taped, making tight joints over the entire ceiling. The acoustical tile is then screwed to the Acousti Lock Board surface.

The Celotex Metal Suspension System consists of specially designed H-Runners, the lower flanges of which engage in a horizontal kerf along the side edge of acoustical tile units, and T-Splines applied at right angles to the H-Runners which engage similar kerfs in the other sides of the tile. The T-Splines rest on the lower flanges of the H-Runners. This method of construction permits furring down an acoustical tile ceiling to any desired level. The H-Runners are attached to regular 1½″ channels spaced 4′ 0″ o. c. Lath and plaster are omitted in this construction. The H-Runners and T-Splines form a metal seal against breathing around all four edges of each tile.

Acousteel is a combination of perforated metal facing material with an enclosed sound-absorbing element. The units are locked in place by engaging in special metal furring which may be fastened to channels or directly against the ceiling or wall.

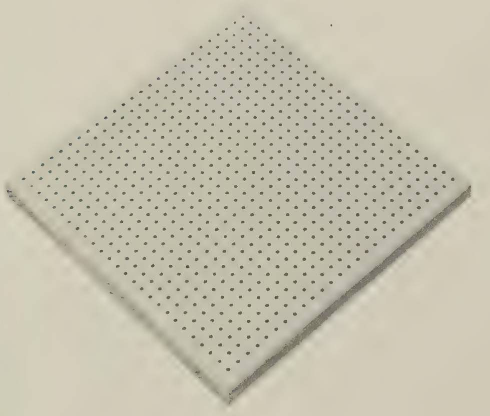
Sears Roebuck & Company Department Store, Compton, California. Acousti-Celotex tile was applied to Acousti Lock Board.

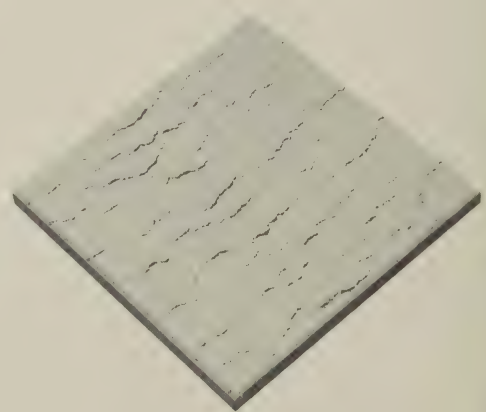




ACOUSTI-CELOTEX CANE FIBRE TILE is a light weight, rigid unit, combining acoustical efficiency with a durable, smooth surface. Perforations (to within 1/8" of the back) assure repeated paintability and ease of maintenance. Available in a variety of sound-absorbent ratings. Rot proof and vermin proof (patented Ferox Process).

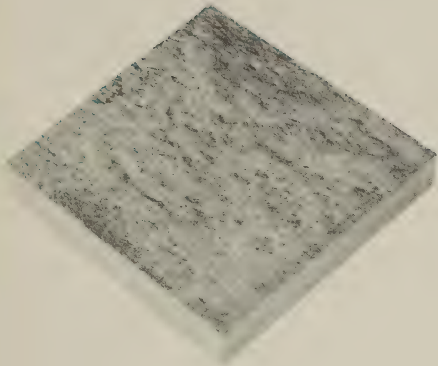
ACOUSTI-CELOTEX FLAME RETARDANT TILE is a cane fibre tile with a flame retardant surface. This tile meets all requirements for *Slow Burning* rating as stipulated in Federal Specifications SS-A-118a. It may be washed or repainted without imparing its flame retardant characteristics - and without loss of sound absorbing capacity.



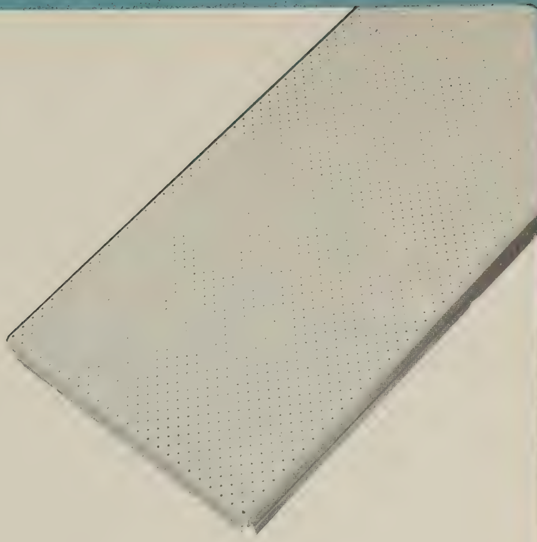


ACOUSTI-CELOTEX MINERAL TILE is made of mineral fibre, felted with a binder to form a rigid tile with a universal rating of incombustibility. Perforated with small holes extending almost to the back of the tile, high acoustical absorption is provided together with unrestricted paintability by either brush or spray method.

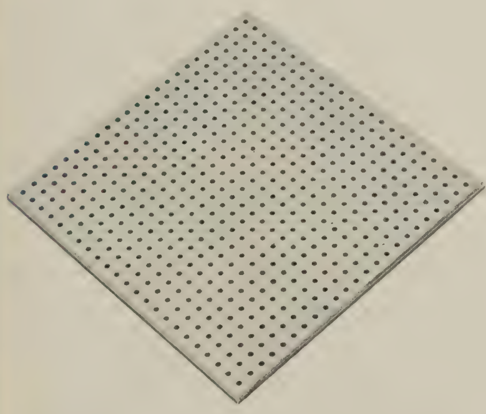
ACOUSTI-CELOTEX FISSURETONE is a mineral fibre acoustical tile. Attractively styled to simulate travertine, it beautifies any interior and effectively controls sound reverberation. Light-weight, rigid and incombustible, it is factory-finished in a soft, flat white of high light-reflection rating. The fissured surface can be cleaned and painted with brush or spray.



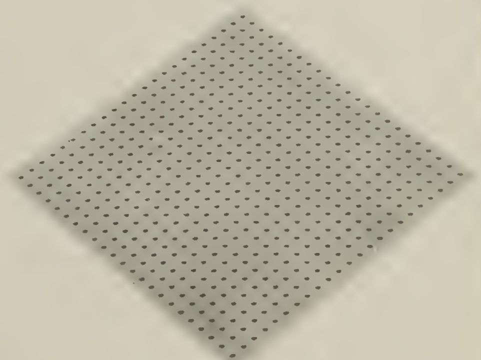
Q-T DUCTLINER is an acoustical material designed especially for use in absorbing sounds usually transmitted through ventilating and air-conditioning ducts. It is composed of rock wool with a special binder, and is made in a rigid block form. It will not support combustion, is moisture-proof and has a low thermal conductivity.



ACOUSTEEL combines a face of perforated steel with a rigid pad of sound absorbing rock wool to provide excellent sound absorption, together with attractive appearance, durability and incombustibility. The exposed surface of perforated steel is finished in baked-on enamel. Acousteel is paintable, washable and cleanable.



PERFORATED ASBESTOS BOARD is a fireproof material made from Portland cement and asbestos fibres. It has a smooth, hard finish, light gray in color. Edges are beveled or square cut. Made for use as a sound-transparent material in combination with rock wool or other sound absorbing units.



PERFORATED PANEL BOARD is a hardboard (wood fibre) product containing a smooth, natural brown finish. It is $\frac{1}{8}''$ in thickness and is made with beveled edges. It is used with a sound-absorbing pad, usually rock wool. Is moisture and abrasion resistant.

TABLE 1. ABSORPTION COEFFICIENTS AND SPECIFICATIONS OF
CELOTEX ACOUSTICAL PRODUCTS

Reprinted by permission from Bulletin No. XI of the Acoustical Materials Association, 1949

Types of Mounting

1. Cemented to plaster board. Considered equivalent to cementing to plaster or concrete ceiling.
2. Nailed to 1" x 3" wood furring 12" o.c. unless otherwise indicated.
3. Attached to metal supports applied to 1" x 3" wood furring.
6. Laid on 24 ga. sheet iron, nailed to 1" x 3" wood furring 24" o.c.
7. Mechanically mounted and special metal supports.

MATERIAL	Thickness	Mounting	COEFFICIENTS						Noise Red. Coef.	Unit Size Tested	Light Reflection		Wt. Lbs. per Sq. Ft.	SURFACE	Test No.
			128	256	512	1024	2048	4096			Color	Value			
ACOUSTI-CELOTEX															
Type C-1	½"	1	.10	.24	.63	.61	.63	.63	.55	12"x12"	I	.78	.81	Perforated[1], painted[2]	A48-79
Type C-2	⅝"	1	.09	.26	.69	.86	.67	.62	.60	12"x12"	I	.78	.83	Perforated[1], painted[2]	A47-76
Type C-2	⅝"	2	.12	.51	.65	.73	.66	.58	.65	12"x12"			.83	Perforated[1], painted[2]	A47-75
Type C-4	1¼"	1	.14	.42	.99	.74	.60	.50	.70	12"x12"	I	.78	1.34	Perforated[1], painted[2]	47-4
Type C-4	1¼"	2	.25	.58	.99	.75	.58	.50	.75	12"x12"			1.34	Perforated[1], painted[2]	47-3
Type C-4	1¼"	7	.53	.58	.93	.70	.55	.48	.70	12"x24"	W	.81	1.58	Perforated[1], painted[3]	46-65
Type C-6	1¼"	1	.15	.34	.99	.94	.61	.61	.70	12"x12"	W	.76	1.51	Perforated[4], painted[3]	46-64
Type C-6	1¼"	2	.27	.57	.91	.91	.67	.58	.75	12"x12"			1.51	Perforated[4], painted[3]	46-63
Type C-7	1"	7	.41	.48	.68	.79	.75	.55	.70	12"x24"	I	.78	1.40	Perforated[1], painted[2]	46-66
Type C-8	1"	1	.18	.35	.86	.87	.63	.56	.70	24"x24"			1.31	Perforated[1], painted[2]	A48-55
Type C-8	1"	2	.25	.49	.69	.78	.61	.48	.65	24"x24"	W	.81	1.54	Perforated[1], painted[3]	46-39
Type C-9	¾"	1	.11	.23	.80	.93	.58	.50	.65	12"x12"	I	.78	.96	Perforated[1], painted[2]	46-132
Type C-9	¾"	2	.12	.45	.79	.89	.61	.60	.70	12"x12"			.96	Perforated[1], painted[2]	46-131
Type M-1	⅝"	1	.07	.21	.64	.86	.93	.83	.65	12"x12"	W	.80	1.31	Perforated[5], painted[3]	46-12
Type M-1	⅝"	2	.12	.48	.50	.79	.93	.82	.70	12"x12"			1.31	Perforated[5], painted[3]	46-11
Type M-2	1"	1	.08	.27	.92	.95	.80	.71	.75	12"x12"	W	.80	1.81	Perforated[5], painted[3]	46-44
Type M-2	1"	7	.40	.44	.79	.99	.77	.71	.75	12"x24"	W	.80	2.23	Perforated[5], painted[3]	46-130
FISSURETONE	¾"	1	.16	.33	.68	.75	.80	.75	.65	12"x12"	W	.79	1.52	Fissured, painted	A48-95
MUFFLETONE															
Standard	1"	1	.12	.30	.74	.76	.71	.67	.65	12"x12"			1.80	Integrally colored	46-24
Fissured	1"	1	.09	.29	.83	.97	.77	.71	.70	12"x12"			1.92	Integrally colored	46-67
ACOUSTEEL															
Pad	1¼"	3	.25	.52	.99	.99	.81	.60	.85	12"x24"				Perforated, enameled metal[6].	46-13
Plus Spacers and metal facing	1⅝"												Pad 1.08		
Plus furring	2½"														
Q-T DUCTLINER	½"	6	.09	.39	.39	.73	.83	.88	.60	24"x36"			.7	Unpainted	A48-9
Q-T DUCTLINER	1"	6	.21	.42	.71	.86	.79	.75	.70	24"x36"			1.3	Unpainted	A48-10
ACOUSTICAL PANEL ASSEMBLY															
Q-T Element	½"		.21	.51	.73	.83	.91	.76	.75	24"x24"			.7	Perforated[7], Unpainted	A48-35
Plus Perforated Asbestos Board Facing	15/16"	See Note 8											1.3		
Q-T Element	1"		.45	.49	.76	.89	.89	.71	.75	24"x24"			1.3	Perforated[7], Unpainted	A48-42
Plus Perforated Asbestos Board Facing	1 1/16"	See Note 9											1.3		

NOTE 1. Perforated 441 holes per sq. ft., 3/16" diameter, 17/32" o.c.
NOTE 2. Face painted before perforating.
NOTE 3. Painted after perforating.
NOTE 4. Perforated 441 holes per sq. ft., ¼" diameter, 17/32" o.c.
NOTE 5. Perforated 676 holes per sq. ft., 5/32" diameter, 7/16" o.c.
NOTE 6. Acousteel is a perforated, enamelled metal pan backed with mineral wool sound absorbing pad. Perforations are .093" diameter, 1105 holes per sq. ft. Bevels and flanges unperforated.
NOTE 7. Facing perforated 576 holes per sq. ft., 3/16" diameter. ½" o.c.
NOTE 8. Element spaced 1½" from backing, 3/16" perforated facing spaced ¼" from element.
NOTE 9. Element spaced 2½" from backing, 3/16" perforated facing spaced ¼" from element.

TABLE II. COEFFICIENTS OF GENERAL BUILDING MATERIALS

Complete tables of coefficients of the various materials that normally constitute the interior finish of rooms may be found in the various books on architectural acoustics. The following short list will be useful in making simple calculations of the reverberation in rooms.

Material	*Coefficients*		
	128	512	2048
Brick wall, painted	.012	.017	.023
Same, unpainted	.024	.03	.049
Carpet, unlined	.09	.20	.27
Same, felt lined	.11	.37	.27
Fabrics, hung straight			
Light, 10 ozs. per sq. yd.	.04	.11	.30
Medium, 14 ozs. per sq. yd.	.06	.13	.40
Heavy, draped, 18 ozs. per sq. yd.	.10	.50	.82
Floors			
Concrete or terrazzo	.01	.015	.02
Wood	.05	.03	.03
Linoleum, asphalt, rubber or cork tile on concrete.		.03—.08	
Glass	.035	.027	.02
Marble or Glazed Tile	.01	.01	.015
Openings			
Stage, depending on furnishings		.25—.75	
Deep balcony, upholstered seats		.50—1.00	
Grills, ventilating		.15—.50	
Plaster, gypsum or lime, smooth finish on tile or brick	.013	.025	.04
Same, on lath	.02	.03	.04
Plaster, gypsum or lime, rough finish on lath	.039	.06	.054
Wood Paneling	.08	.06	.06

ABSORPTION OF SEATS AND AUDIENCE

Audience, seated, units per person, depending on character of seats, etc.	1.0—2.0	3.0—4.3	3.5—6.0
Chairs, metal or wood	.15	.17	.20
Wood Pews		.40	
Pew Cushions (without pews)	.75—1.1	1.45—1.90	1.4—1.7
Theatre and Auditorium Chairs			
Wood veneer seat and back		.25	
Upholstered in leatherette		1.6	
Heavily upholstered in plush or mohair		2.6—3.0	
Heywood Wakefield Co.			
T-C 700 Encore Chairs, fully upholstered—seats held in "up" position by springs (Test No. 48-73)	3.7	3.8	3.5

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